NASA CONTRACTOR REPORT

NASA CR-762

FIRST AND SECOND SIMULATOR EVALUATIONS OF ADVANCED INTEGRATED DISPLAY AND CONTROL SYSTEMS

by J. E. Burke, R. D. Huchingson, R. J. Koppa, and H. E. Sewell, Jr.

Prepared by
LING-TEMCO-VOUGHT, INC.
Dallas, Texas
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1967

NASA CR-762

FIRST AND SECOND SIMULATOR EVALUATIONS OF ADVANCED INTEGRATED DISPLAY AND CONTROL SYSTEMS

By J. E. Burke, R. D. Huchingson,
R. J. Koppa, and H. E. Sewell, Jr.

Prepared under Contract No. NASw-611 by
LING-TEMCO-VOUGHT, INC.
Dallas, Texas

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This report was prepared under NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems - Simulation Phase, for the Office of Advanced Research and Technology, Biotechnology Division. Mr. L. O. Anderson is Technical Monitor for the program. The simulation programs described herein were initiated in August 1965 and completed in July 1966.

The authors wish to acknowledge the assistance of Mr. G. W. Hoover, LTV Consultant for Man-Machine Systems, in the application of analog display concepts.

Appreciation is extended to the following for their efforts in providing special equipment for the program; Norden Division of United Aircraft, suppliers of the Pathway Display System Demonstrator; Master Specialties Company, suppliers of cockpit switchlights; and Industrial Electronics Engineers, Inc., suppliers of the status-trend display.

The pilots who participated in the experimental simulation program included LCdr J. R. Burriss, LCdr H. H. Love, and LCdr R. L. Mock, of the Bureau of Naval Representative Office at LTV.

ABSTRACT

This report describes the first two simulator evaluations in a program to define advanced integrated display-control requirements for post-Apollo space vehicles. The test program was conducted in the LTV Manned Aerospace Flight Simulator employing a Space Analog Vertical Display and Horizontal Display, space vehicle subsystems status-trend information, and dynamic simulation of motion and auditory cues. The two simulations differed primarily in the types of information presented on the Vertical Display: the First Evaluation featuring command attitude information and the Second Evaluation presenting information on deviation of the vehicle flight path (velocity vector) from the required (Nominal)path. The report describes in detail the simulation problem, hardware setup including equations, procedure, measurements, test data, and interpretation of tests of significance and pilot questionnaires. The results of the first two simulations demonstrate that the Space Analog Display is a feasible means of control of space vehicles during orbital maneuvers with median injection point data on relevant parameters generally within currently anticipated allowable errors. Comparisons are made between various variables both within and between evaluations and recommendations are provided for further improvement of the display presentation for future evaluation.

SUMMARY

The first two simulator evaluations in a program to define advanced integrated display-control requirements for post-Apollo space vehicles are described. This includes the simulation setups in the LTV Manned Aerospace Flight Simulator (MAFS); selection, grouping, and indoctrination of test subjects; experimental testing procedures; data recording, analysis, and results.

FIRST EVALUATION

During the period 28 January through 14 February 1966, a total of 172 experimental flights were flown in the LTV MAFS by six, currently qualified jet pilots. A prime objective of this simulation was the evaluation of a space analog vertical display, featuring a vehicle attitude command presentation during thrusting, in a cisplanetary injection maneuver. Concurrently, the need for supplementary digital information, command attitude display gain in various forms, and the effects of acceleration versus rate attitude control on pilot performance were evaluated.

Test results indicate that this analog format, in a standard television presentation, is a feasible means for performing the injection maneuver.

However, the command attitude format did not provide adequate task performance information ("How am I doing?"). The pilot had to place complete reliance in the attitude command during the thrusting maneuver which had to be completed before the success of the maneuver could be ascertained.

Supplementary digital information did not improve pilot performance.

The use of display gain in the attitude command presentation had little effect upon attitude control performance.

Use of the acceleration attitude control mode was deleted early in the simulation program when it was determined that the vehicle was virtually unmanageable in this mode. The angular rates achieved could not be effectively compensated for by the pilot and rapidly reached the limits of scaling in the digital computer. Pilot opinion was that this mode could be learned, but not without considerable practice. Rate attitude control was used for all subsequent flights.

The space analog format was well received and comparatively inexperienced pilot and even non-pilots learned to make an acceptable injection in just a few trials.

The prime recommendation made as a result of the First Evaluation was to revise the vertical display format during the thrusting phase to add task performance information. It was recommended that the command attitude presentation be replaced by a more natural format incorporating the presentation of the space vehicle direction of motion with respect to the required (Nominal) path.

In this format task performance formation would always be available in that the effects of pilot control of vehicle attitude and thrust are presented in the form of vehicle position and direction of motion with respect to the required path.

SECOND EVALUATION

During the period 27 June through 13 July 1966, a total of 84 experimental flights were flown in the LTV MAFS by six, currently qualified pilot subjects. A prime objective of this simulation was the evaluation of a space analog vertical display wherein the view is in the direction the space vehicle is moving, and is in proper relationship to the required (Nominal) path, and a background representative of the real world.

Three experimental questions were evaluated concurrently:

(1) Was display gain required in presenting vehicle path elevation and heading errors;

(2) What were the effects upon pilot performance when attaining the cisplanetary injection point from initial on-path versus off-path positions; and

(3) What were the effects upon pilot ability to acquire the Nominal path when using a path display incorporating a single-scale range of vehicle positional error versus one with a three-scale display of the same range (altitude and lateral position)?

The flight problem, and other aspects of the simulation setup were the same as in the First Evaluation to permit a direct comparison of pilot performance between the Space Vehicle Command Attitude display format of the First Evaluation and the Space Vehicle Path format of the Second.

Test results indicate that this analog format, in a standard television presentation is a feasible means for performing the injection maneuver. However, certain deficiencies were noted in the use of fixed display gain and in the presentation of certain analog display elements, which when corrected should result in a higher level of performance.

The Space Vehicle Path Mode was not flyable when vehicle flight path elevation and heading errors were presented in a 1:1 relationship with the real world. Gains of 6:1 in elevation and 32:1 in heading were used to achieve the results reported herein.

Pilot performance with vehicle on-path initial conditions was superior to that with off-path initial conditions.

Overall pilot performance (all parameters) was superior when using the single-scale path display, except for lateral position error control where the three-scale configuration was superior.

The prime recommendation made as a result of the Second Evaluation is to investigate techniques for providing a logarithmic increase in display sensitivity as error is decreased and a decrease in sensitivity as error is increased. Parameters affected would include vehicle flight path elevation and heading errors and altitude and lateral position errors. In addition, in order that the pilot may anticipate the consequences of vehicle attitude control inputs, it is recommended that quickening and/or prediction be investigated and incorporated.

COMPARISON BETWEEN THE FIRST AND SECOND EVALUATION

Four of the six flight performance parameters favoring the First Evaluation were highly significant (0.02 or better). These parameters were elevation error, heading error, altitude error, and roll energy expenditure. The level of significance for a fifth parameter, lateral error, could not be assessed because the First Evaluation reported this error as essentially zero. The sixth parameter, velocity error, was significant at a very low level (0.18). An explanation for the superior performance on these parameters in the First Evaluation was the extremely fine display sensitivity to small errors which was achieved through the use of a command attitude presentation.

The three parameters favoring the Second Evaluation were highly significant (0.06 or better). These parameters were longitudinal error, pitch and yaw energy expenditure. An explanation for the lower control energy expenditure in pitch and yaw was that in the First Evaluation pilots tended to overcontrol by correcting for insignificant errors, whereas in the Second Evaluation pilots were less aware of very small deviations from an idealized vehicle flight path and, therefore, corrected much less often.

A comparison of injection point data with representative space system performance requirements is shown below. System requirements listed as allowable errors for interplanetary missions are based on the EMPIRE Program and Apollo. These requirements are the best available at the present time and subject to revision and more exact definition as interplanetary planning advances.

Parameter		Median Errors* First Evaluation	Median Errors** Second Evaluation	Allowable Interplanetary Errors
Flight Path Elevation	(DEG)	0.0025	0.192	0.10
Flight Path Heading	(DEG)	0.003	0.009	0.10
Velocity	(FPS)	5.0	7.3	4-10
Lateral Position (out-of-plane)	(FT)	Essentially Zero	1,027	50-11,000
Longitudinal Position (in-plane)	(FT)	6,441	1,181	50-11,000
Altitude	(FT)	121	4,368	3,000
Energy Expenditure (attitude control)				
Pitch	(%)	29.0	13.68	N/A
Yaw	(%)	24.3	8.28	N/A
Roll	(%)	4.6	5.48	N/A

* Grand median error
**On-path, 1-scale median errors

PROGRAM RECOMMENDATIONS

The Second Evaluation has defined the need for further research in specific areas which should result in a higher level of pilot performance. This research can be accomplished with equipment and facilities presently available to the program with required but limited modifications in certain specific areas. It is therefore recommended that a Third Evaluation be conducted in the LTV Manned Aerospace Flight Simulator (MAFS) to correct the deficiencies in the Space Analog that have been identified.

The objectives of the Third Evaluation will be:

(1) Improve the natural (realistic) presentation of space vehicle flight path angular and positional errors with respect to a required (nominal) path by investigating techniques for providing a logarithmic or non-linear increase in display sensitivity as error is decreased and a decrease in sensitivity as error is increased.

(2) Improve displayed vehicle flight path response to attitude control when thrusting by investigating techniques for incorporating quickened and/or predictor forms of information in the Space Analog to compensate for the inherent lag between pilot attitude control inputs and the visible change in vehicle flight path.

(3) Revise the Vertical Display System Demonstrator equipment to correct deficiencies in display element presentation.

(4) Incorporate an Earth capture flight profile, in lieu of the cisplanetary injection profile previously used, to extend the investigation of the operational capabilities of the Space Analog to another critical phase of the space mission.

(5) Investigate pilot ability to recognize malfunctions of the Space Analog by observation of display element performance (through programmed random deviations from the natural environmental format) in the course of normal space flight operation; and to identify and correct such system malfunctions through the interpretation of advanced integrated forms of vehicle subsystem status information appearing on the Horizontal Display, and applicable panel controls. This will serve as a more realistic form of operational pilot task loading than the first level of information Status-Trend display used during the first two simulator evaluations.

(6) Define the envelope of flight operation for the Vertical Display portion of the Space Analog, i.e., what are the limits, if any, in off Nominal Path vehicle conditions, which retain a natural environmental format and do not require supplementary planning information for normal flight operation?

It is expected that the Third Evaluation will produce the following results:

(1) The deficiencies of the Space Vehicle Path Mode defined in the Second Evaluation will be corrected and the resultant pilot flight performance

will compare closely with that of the Space Vehicle Command Attitude Mode of the First Evaluation. Further, it will be shown that the Space Analog concept of information presentation meets the requirements of current and future space systems in a manner that permits maximum manned participation and decision making during the most critical phases of space flight.

(2) Demonstration of a pilot's ability to recognize and correct possible malfunctions in the Space Analog will increase confidence and acceptance of this form of information presentation.

(3) The application of advanced integrated information presentation to vehicle subsystem malfunction detection and correction, used in conjunction with Space Analog malfunction recognition and as pilot task loading, will demonstrate the advantages of these concepts in this area.

CONTENTS

Page

Page

FIGURES

FIGURES (contd.)

TABLES

1.0 INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

In future space systems, man and his machine will require much more integration than is presently being achieved to (1) maximize capabilities in space operations, and (2) to permit the design of more functional and reliable equipment. One area where sufficient information is presently not available to provide an adequate understanding of the man-machine interface, is in crew station displays and controls.

Considerable research has been conducted in the past by various government organizations which has not been thoroughly evaluated for application to space vehicles, and until the introduction of realistic simulation, no adequate means has been available for such evaluation. A basic tool in the present effort is the LTV Manned Aerospace Flight Simulator (MAFS), which permits the required evaluations to be conducted under dynamic space flight conditions.

1.2 PROGRAM OBJECTIVES

The objectives of this program are:

(1) To define, evaluate, and validate, in an objective manner, advanced display and control systems concepts that will maximize man's capabilities in the man-machine interface of advanced space systems.

(2) To provide proven display-control system requirements thereby assuring an early optimization of the man-machine interface and a marked reduction in equipment development time.

1.3 TECHNICAL APPROACH

To date this program has accomplished the following:

(1) Examined contemplated manned space missions subsequent to Apollo and established a generalized flight profile that encompasses the situations relating to future space flights and is a suitable base for the evaluation of advanced systems (Reference 1).

(2) Reviewed existing data on the most effective current methods of presenting basic types of information to man and determined their initial application to space flight (Reference 2).

(3) Conducted mission, function and task analyses of the generalized flight profile and established initial vehicle systems display and control requirements (Reference 3).

(4) Defined an initial integrated display and control configuration, based upon man's fundamental capabilities and limitations, to meet the mission requirements of the generalized flight profile.

(5) Simulated this initial display and control configuration and evaluated display configuration performance under dynamic space flight conditions in the LTV MAFS.

(6) Evaluated the results of simulation and recommended further studies needed. (This report.)

Studies (1) through (4) above, were accomplished as part of the Requirements Analysis Phase of this program which is summarized in Reference 4.

A schematic of the program to date is shown in Figure 1.

1.4 GENERAL EVALUATION PLAN

In the Requirements Analysis Phase, post Apollo space missions were first reduced to a generalized flight profile and then to basic flight phases and fundamental information and control requirements. Concurrently, advanced display and control concepts developed by previous investigators were reviewed and the most promising selected for incorporation, evaluation, and further development. The culmination of this analytic effort was an initial definition of displays and controls which serves as the base configuration for further development through realistic six-degrees-of-freedom simulation in the LTV MAFS. By operational evaluation and development through all the flight phases of the generalized flight profile, optimized integrated system requirements are being defined along with supporting simulation data.

Each simulation phase of this program consists of the following:

(1) Definition of a display-control configuration incorporating the concepts to be evaluated, a related flight phase environment, and test objectives.

(2) Implementation of a simulator setup including: MAFS crew station hardware, vehicle equations of motion, computer equations, supporting computer programming, test experimental design, subject selection, test data requirements, data evaluation procedures, computer hardware setup and engineering shakedown of the simulation complex.

(3) Formal testing.

(4) Test data evaluation.

(5) A report, containing a description of the simulation complex, test conclusions, identification of concepts validated, and recommendations for additional analysis and testing of concepts requiring further development.

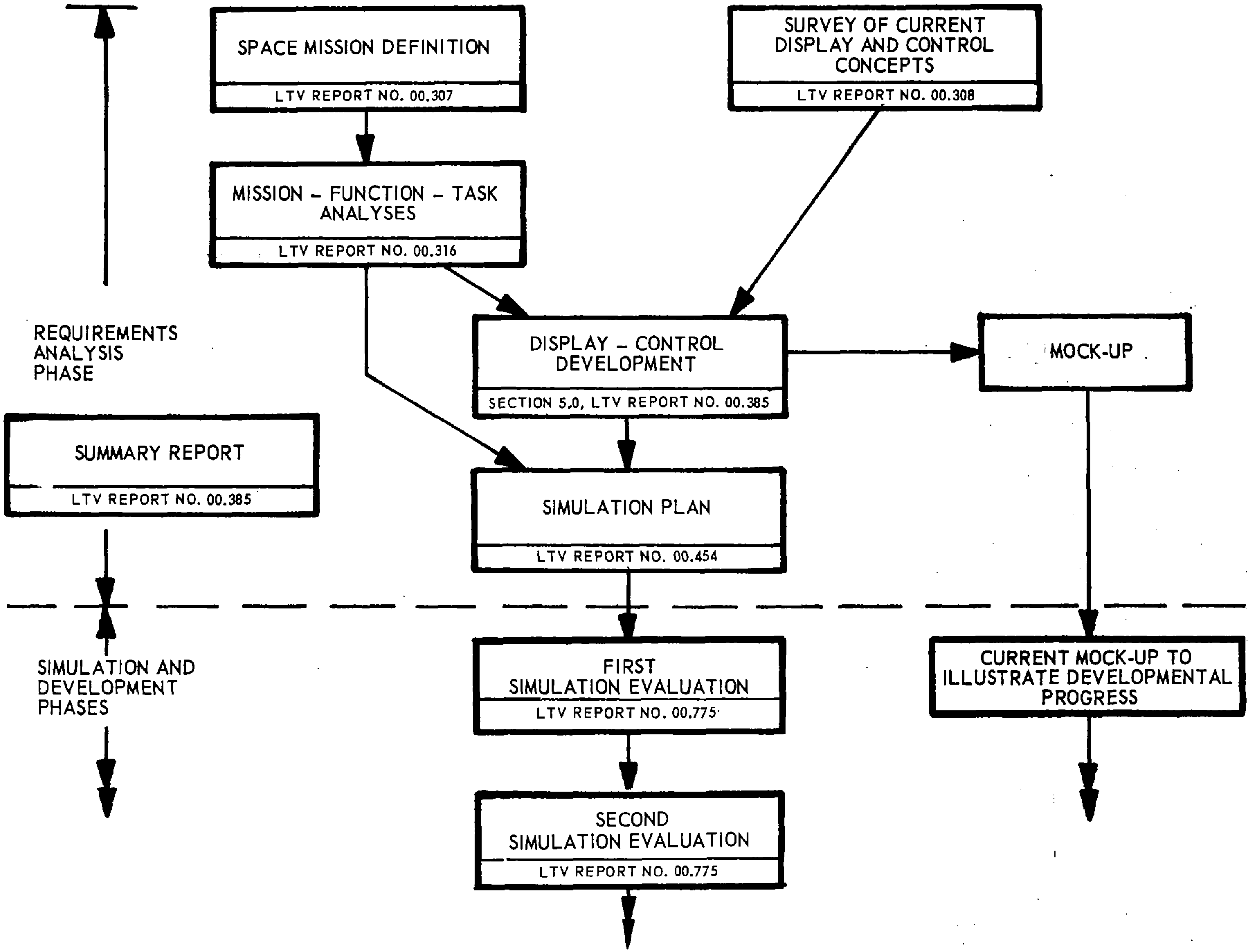


FIGURE 1 PROGRAM SCHEMATIC

1.5 REPORT FORMAT

This document reports on the results of two separate simulation evaluations, for the purpose of comparing the operational performance of two analog displays: one presenting command attitude flight information, similar to that available in current space programs (First Evaluation); the other an advanced integrated Space Analog incorporating a natural environmental format (Second Evaluation).

The greater part of the simulation setup is common to both evaluations, the differences in display presentations being accomplished by changes in the computer programming. Descriptions of equipment used, procedures, etc., appearing in the First Evaluation section of this report are also applicable to the Second, except for those differences noted in the Second Evaluation section.

The body of this report defines equipment, procedures and techniques used; presents examples of data taken, descriptions of analyses, and the resulting conclusions and recommendations. Additional supporting data is presented in the appendices.

2.0 FIRST EVALUATION

The purpose of the First Evaluation was to establish the operational effectiveness of an analog vertical display when presenting flight information similar to that in current space programs both with and without numerical backup data. The results are to serve as a base for comparison and development of more advanced integrated Space Analog Display requirements. Testing consisted of 172 experimental flights in the LTV MAFS during the period 28 January through 14 February 1966.

2.1 OBJECTIVES

The objectives of the First Evaluation were:

(1) Investigate the ability of a pilot to set up and execute an orbit (or trajectory) change maneuver using command attitude indications, present orientation, and situation data and presented on the Vertical Orientation and Horizontal Situation displays.

(2) Determine what modifications or additional information were required in these initial display configurations to achieve better man-machine integration.

(3) Investigate the effects of different control modes on pilot performance and define the requirements for the most effective control method(s).

(4) Establish requirements for display and control concepts that had been validated through simulation results and/or define the requirements for further investigation.

2.2 THE SIMULATION PROBLEM

2.2.1 The Space Mission Segment

The mission segment selected for the first evaluation program was the critical injection maneuver from earth orbit into a Mars cisplanetary trajectory (Figures 2 and 3). This had been designated as one of the events requiring precise orientation, navigation, and energy management information for the pilot to participate in the control loop with maximum effectiveness. In addition, nearly all maneuvers in space flight (with the exception of proximal docking and non-atmospheric landing), are much like the injection maneuver differing primarily in precise values of the parameters and in the degree of control accuracies required.

The simulation began with the vehicle in a given position in a circular orbit around the earth. The injection was made with reference to a nominal path to Mars. The injection point was constant for attainment of the Mars trajectory.

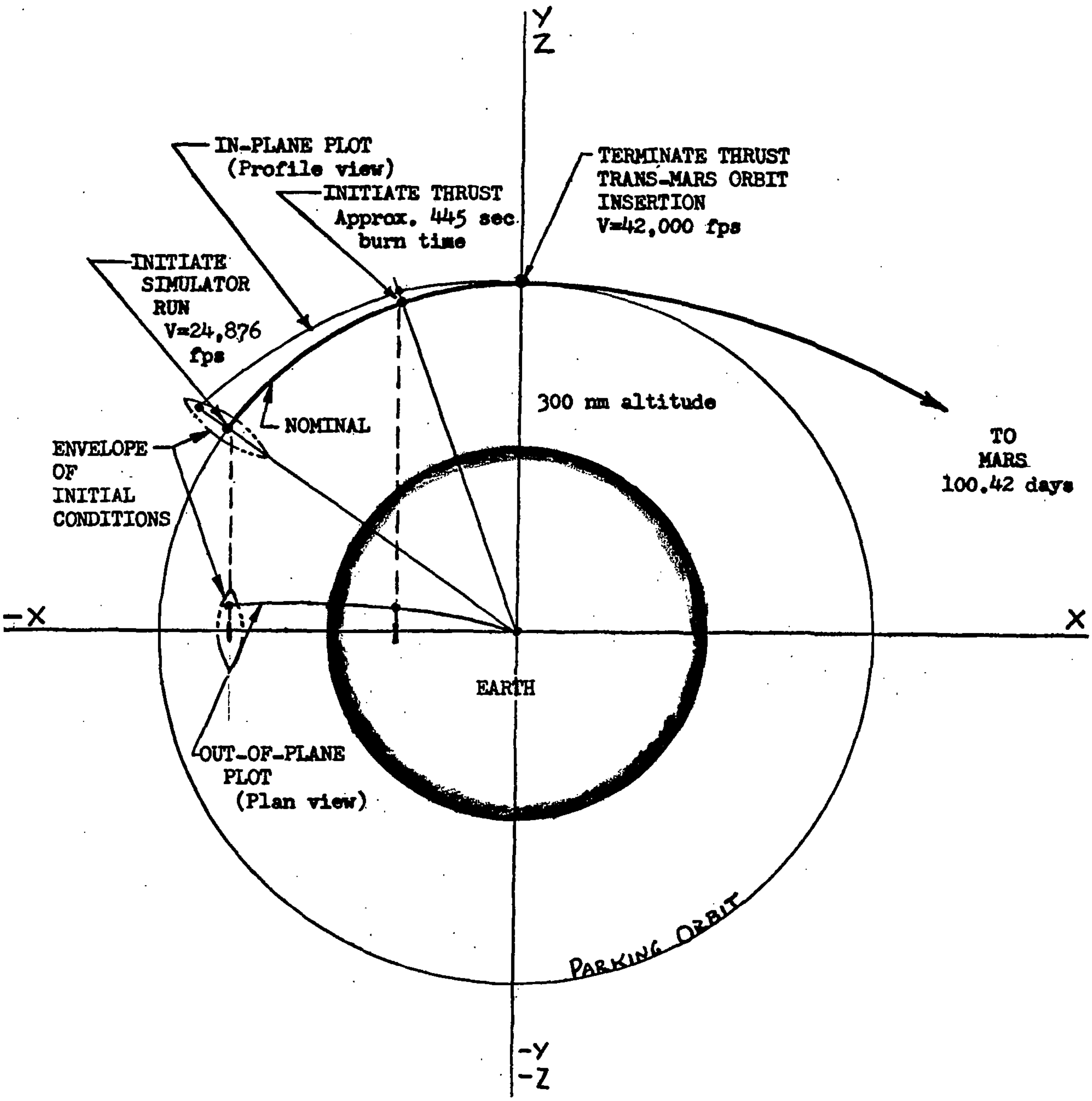


FIGURE 2 NOMINAL INJECTION MANEUVER

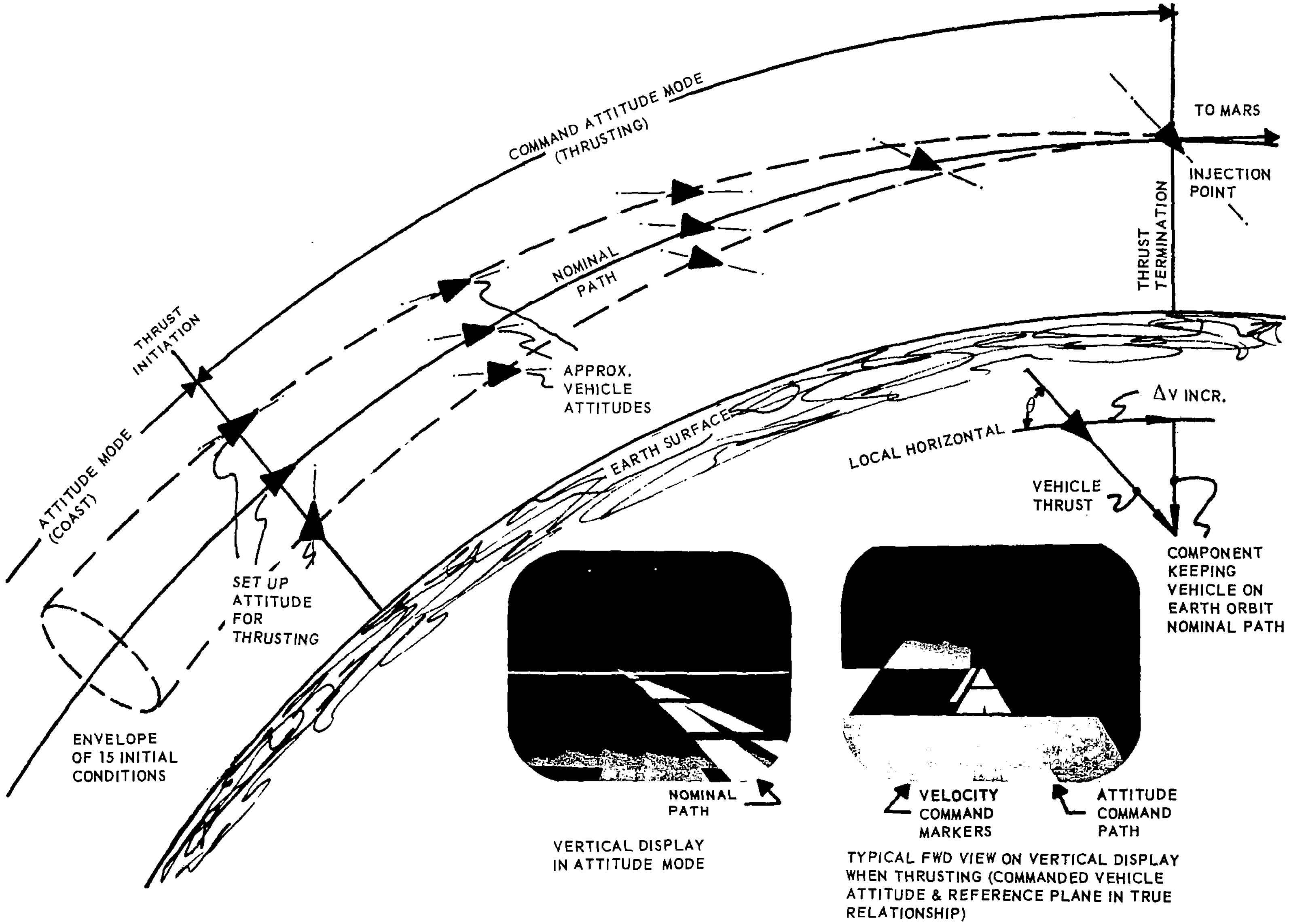


FIGURE 3 TYPICAL FLIGHT PROFILE – FIRST EVALUATION

Each simulation flight was terminated upon shutoff of the main engine (a nuclear fission plant) at injection into the cisplanetary trajectory. Assessment of the success of the injection maneuver was made in terms of correspondence of the terminating position, velocity and flight path angles of the vehicle (its "state") relative to the conditions required at the injection point.

The only crew station considered in the program was the primary pilot-commander station. No navigational operations were carried out by the pilot. The director displays, which command the operator to take specific action, presented information which would, in a realistic situation, be derived from the spacecraft's computer and navigation system. The primary problem herein was to determine (given the information that a pilot would require from a navigation system) the degree to which he could:

(1) Interpret what it is he must do to accomplish the mission goals and,

(2) His effectiveness as a vehicle controller in the man/machine loop utilizing the displays and controls supplied him.

2.2.2 Simulated Space Vehicle

In order to study the utilization of any display-control concept in a mission setting, it was necessary to "invent" a vehicle to convey the simulation with as little bias as possible. This was accomplished by establishing vehicle characteristics typical of most vehicles in its class, and by measuring those performance parameters which were as unrelated to the particular vehicle simulated as possible. Thus, speaking in terms of delta velocity requirements instead of mass losses, acceleration instead of thrust, etc., it will be possible to apply the experimental results to a wide variety of vehicles. Table 1 presents the details of the Simulated Space Vehicle.

SPACEFRAME:	
Shape -	Cylindrical
Symmetry -	About longitudinal axis
ENGINE (MAIN):	
Type -	Nuclear Reaction Turbulent Flow Solid Core Heat-Exchange Fission Gas-generator Turbopump
Propellant -	Hydrogen
Thrust - To Mass Ratio -	At thrust initiation approximately 32.2 ft/sec^2
Location -	Aft; Thrust along longitudinal axis through center of mass*
Operation -	Dichotomous; Full-power or off. Sequence automatic except for initiation. Fixed nozzle.
Specific Impulse -	850 sec.
ATTITUDE CONTROL SYSTEM:	
Type -	Hot Gas Reaction Jets H_2O_2 over Catalyst (monopropellant)
Acceleration Levels -	Pitch: $5^o/sec^2$ Yaw: $5^o/sec^2$ Roll: $5^o/sec^2$
Operating Characteristics:	
Moments-	Jets arranged to produce pure couples
Acceleration Command -	Jet Valve Open or Closed - Fly by wire mode
Rate Command -	Jet Valve Open or Closed - Open time varied for amount of deflection by logic circuit. Sign of a control movement determines direction of thrust. Full thrust attained after ramp function buildup in rate by pulse-modulated system. Permits small deadband.

*Location of C.M. will be varied randomly (as a function of time) during each trial run, simulating fuel mass shift, etc. This will produce thrust misalignment problems.

TABLE 1 SIMULATED SPACE VEHICLE CHARACTERISTICS SUMMARY

2.3 SIMULATION SETUP

Major components included in the simulator implementation were as follows:

2.3.1 LTV Manned Aerospace Flight Simulator (MAFS)

The MAFS is a moving base crew station simulator with the crew station gondola mounted inside a 20-foot diameter sphere. The interior walls of the sphere serve as a projection screen for appropriate visual projection systems. However, external visual displays were not required for this simulation. Crew station gondola motion is provided by four hydraulic powered gimbals - outer pitch, yaw, inner pitch, and roll. The outer pitch motion has a deflection capability of ±100 degrees and primarily provides variations in the longitudinal acceleration on the pilot. Maximum yaw and inner pitch deflections are ±10 degrees. The yaw and inner pitch drives are pivoted 6 feet behind the pilot, the yaw motion providing lateral and yaw accelerations, with inner pitch providing normal and pitch acceleration cues to the pilot. Roll motion, which provides pilot oriented roll accelerations, is limited to ±20 degrees in rotation. The roll axis is 20.5 inches below the normal eye position.

Figure 4 is a view of the simulator room and shows the gondola on the moving base inside the 20-foot diameter sphere with the Safety Engineer's console at left. The purpose of the Safety Console is to monitor operation of the moving base for the protection of personnel and apparatus. Figure 5 presents side views of the gondola, canopy open and closed, as it appeared for this program.

2.3.2 Crew Station Displays and Controls

The crew station display panel is shown in Figure 6. Of this configuration, only the units listed below were required to be operable for this evaluation. These operating units are emphasized in Figure 7. Primary cockpit controls were the vehicle thrust control and the three axis vehicle attitude controller. In addition, the panel contained numerous illuminated legend pushbutton switches and variable rotation controls (submerged wheel type) on both sides of the television displays.

(1) Vertical Display

The vertical display was implemented with the Norden Pathway Display System Demonstrator (Reference 5). This system utilized a 14-inch television tube in the MAFS crew station to display a space analog presentation. The electronically generated scene was a view looking forward over the nose and along the thrust axis of the vehicle. The viewed scene was in 1:1 relationship with the real world with a view angle of 23.7 degrees in the vertical plane and 31.2 degrees in the horizontal plane. The background scene consisted of a ground plane, horizon line, and starfield presentation; for displaying vehicle orientation, velocity and heading relative to the local horizontal plane. In addition, the ground plane grid indicated variations in altitude, the size of the grid varying inversely with altitude. A pathway,

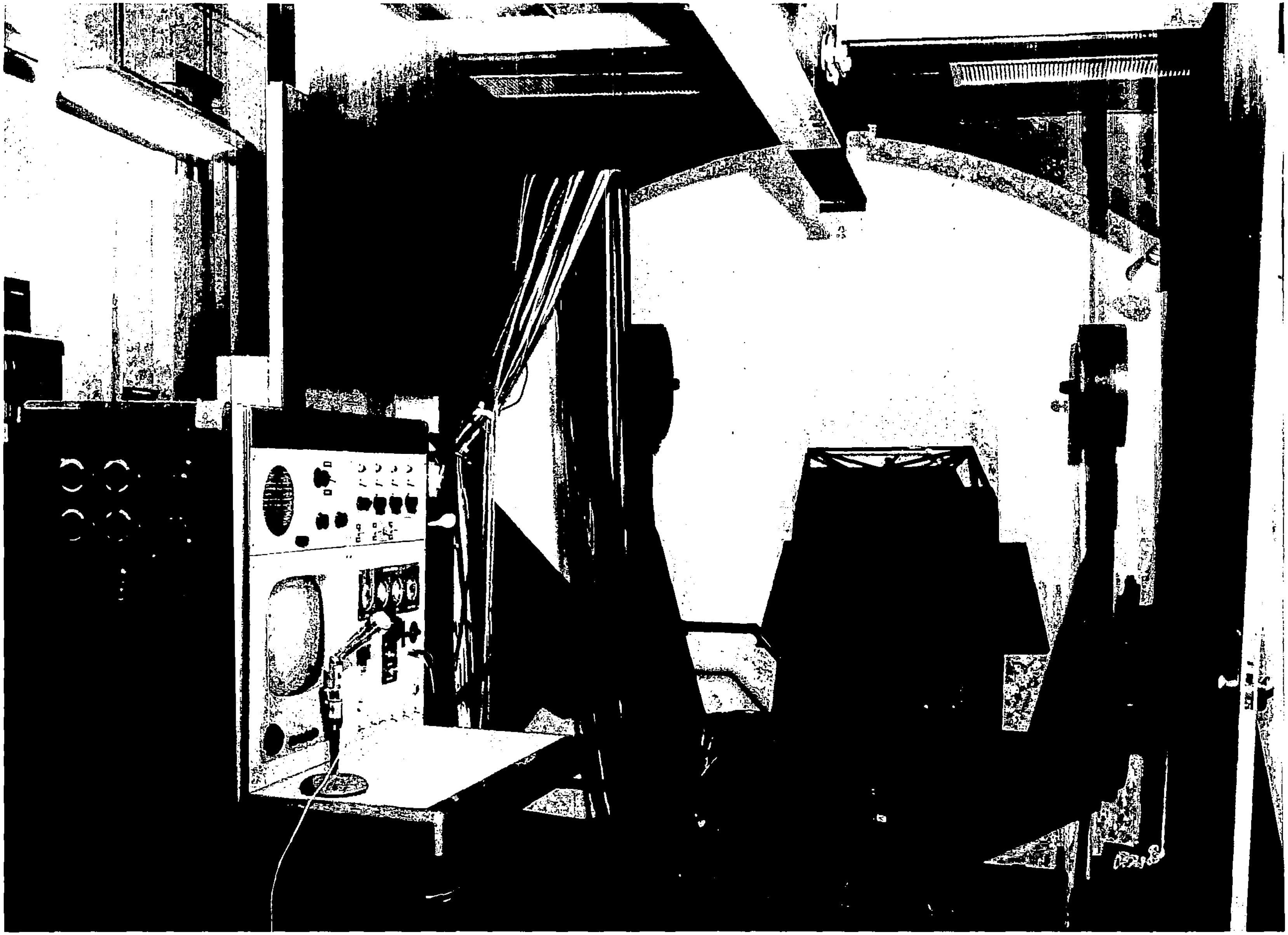


FIGURE 4 LTV MANNED AEROSPACE FLIGHT SIMULATOR (MAFS) – SIMULATION ROOM

CANOPY OPEN

CANOPY CLOSED

FIGURE 5 LTV MAFS CREW STATION GONDOLA

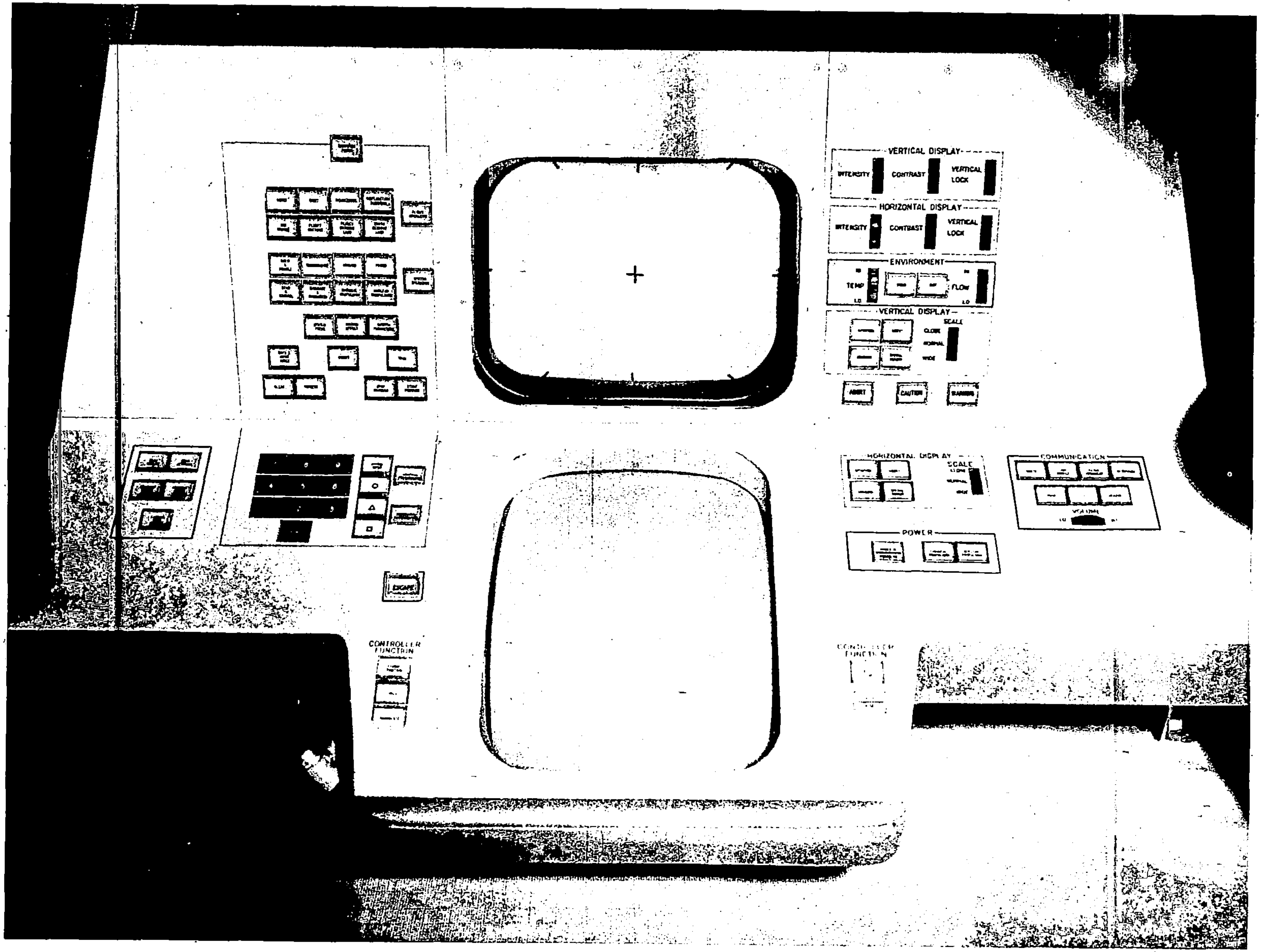


FIGURE 6 LTV MAFS – CREW STATION DISPLAY PANEL

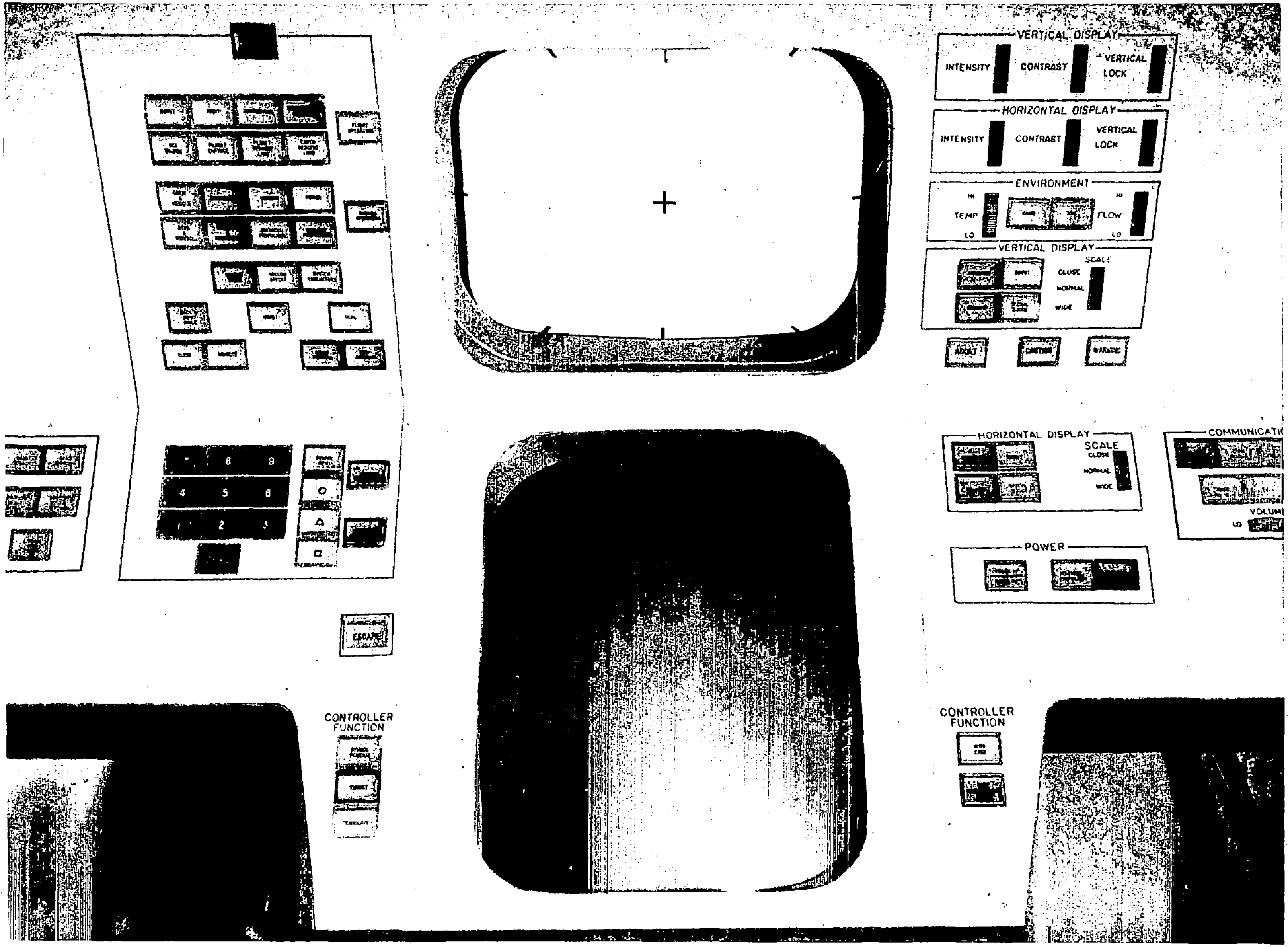


FIGURE 7 OPERATING UNITS ON CREW STATION DISPLAY PANEL

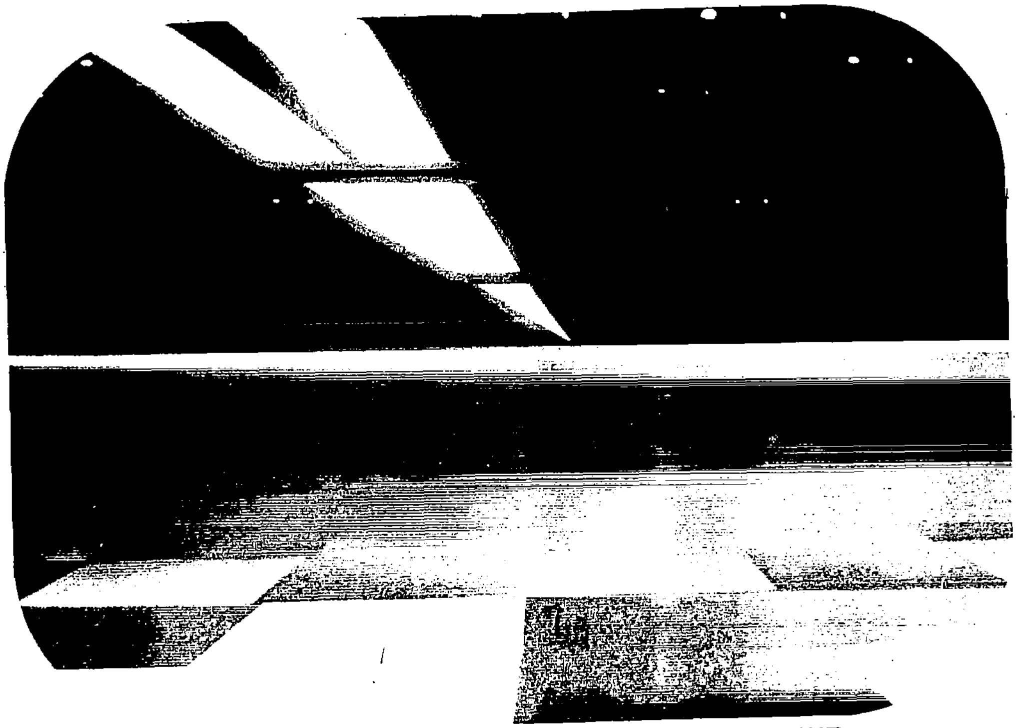
converging at infinity, was superimposed on the background scene with the function of the path varying with the selected display mode - ATTITUDE or COMMAND ATTITUDE. Figures 8 and 9 show typical vertical display presentations for each mode.

(a) Space Vehicle Attitude Mode - In the attitude mode the pathway represented the nominal (or required) orbital path, and conveyed vehicle attitude, velocity, vertical (altitude) and lateral (horizontal) displacements relative to it. For vehicle roll displacements the path rotated with the background scene - i.e., with the ground plane. Vehicle yaw and pitch motions with respect to the path were depicted by rotations of the path with the pilot as the center, and displacement of the path vanishing point (tip) from display center, right - left parallel to the ground plane, and up - down normal to the ground plane, respectively. Vehicle velocity along the path was displayed by bars, "tar strips," across the path, and parallel to the horizon line, which translated along the path. The width of the path varied inversely with altitude error (vehicle altitude relative to that of the nominal path), the near end of the path being full display width for zero altitude error. Direction of altitude error was presented by the relative position of the path with respect to the center of the screen; the path appearing in the lower half of the screen when the vehicle was above the path and vice-versa. The near end of the path was displaced left and right of display centerline parallel to the ground plane for lateral (horizontal) displacement of the vehicle from the nominal path.

(b) Space Vehicle Command Attitude Mode - In the command attitude mode the path presented required attitude at present vehicle position. The near end of the path remained at full width of the display, parallel to the ground plane, and centered in the display (zero altitude error and lateral displacement) representing present vehicle position. Yaw and pitch attitude changes required for controlling to the commanded flight path were presented by lateral displacements of the path tip - by bending the pathway right and left parallel to the ground plane; and vertical displacement of the path tip by rotation of the pathway up and down about its near end normal to the ground plane, respectively. Present velocity was displayed by the "tar strips" as for the Attitude Mode, while the velocity error from the required value was displayed by speed markers, bars adjacent and parallel to the left side of the pathway, which translated along the path at a rate that was a direct function of the velocity error, the direction of motion relative to that of the "tar strips" denoting the error sense.

(2) Horizontal Display

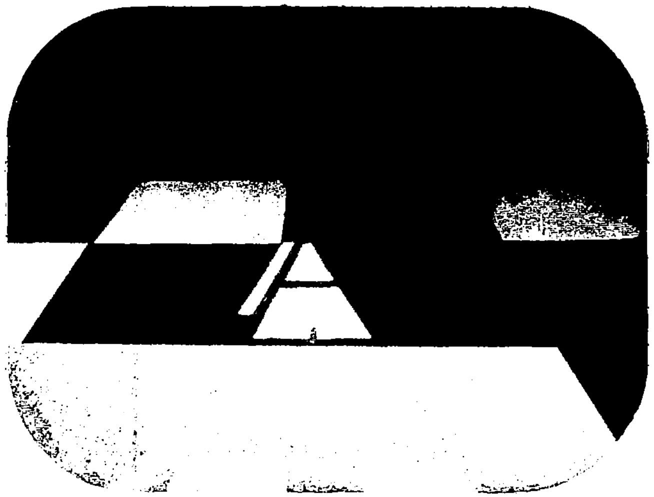
The horizontal display utilized a 16 inch television tube with its long dimension (normally the width) oriented fore and aft. It displayed a composite picture of three basic presentations as shown in Figure 10. The composite scene was obtained via a closed circuit TV camera using a beam splitter, one-way mirror, system as shown in Figure 11. Two of these displays, System Status-Trend and Horizontal Situation, were available for all runs. The third display, Digital Readout, was presented only when specified by the experimental requirements.



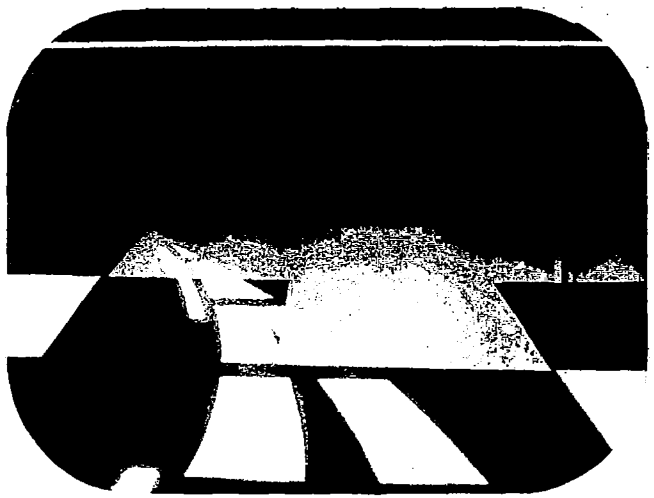
VEHICLE BELOW NOMINAL PATH AND TO THE RIGHT

VEHICLE ABOVE NOMINAL PATH AND TO THE LEFT

FIGURE 8 VERTICAL DISPLAY PRESENTATIONS – SPACE VEHICLE ATTITUDE MODE

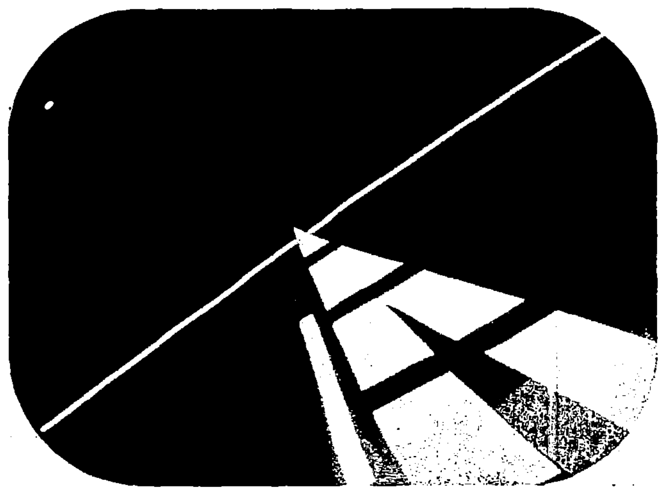


VEHICLE ON COMMAND PATH



VEHICLE ON PATH WITH YAW LEFT COMMAND

VEHICLE ON PATH WITH YAW LEFT COMMAND



VEHICLE ON PATH AND ROLLED TO RIGHT

FIGURE 9 VERTICAL DISPLAY PRESENTATIONS – SPACE VEHICLE COMMAND ATTITUDE MODE – FIRST EVALUATION

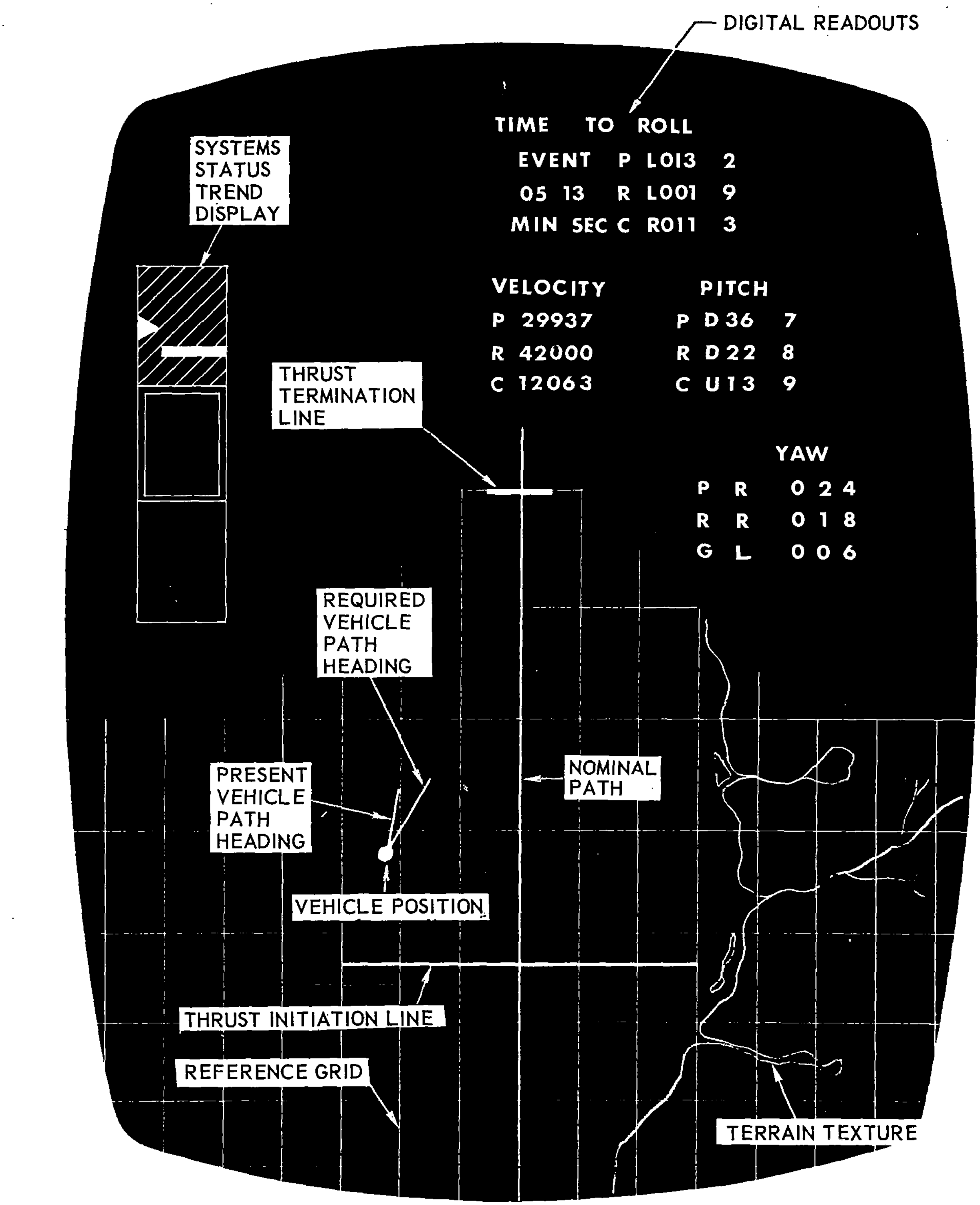


FIGURE 10 HORIZONTAL DISPLAY PRESENTATION – FIRST EVALUATION

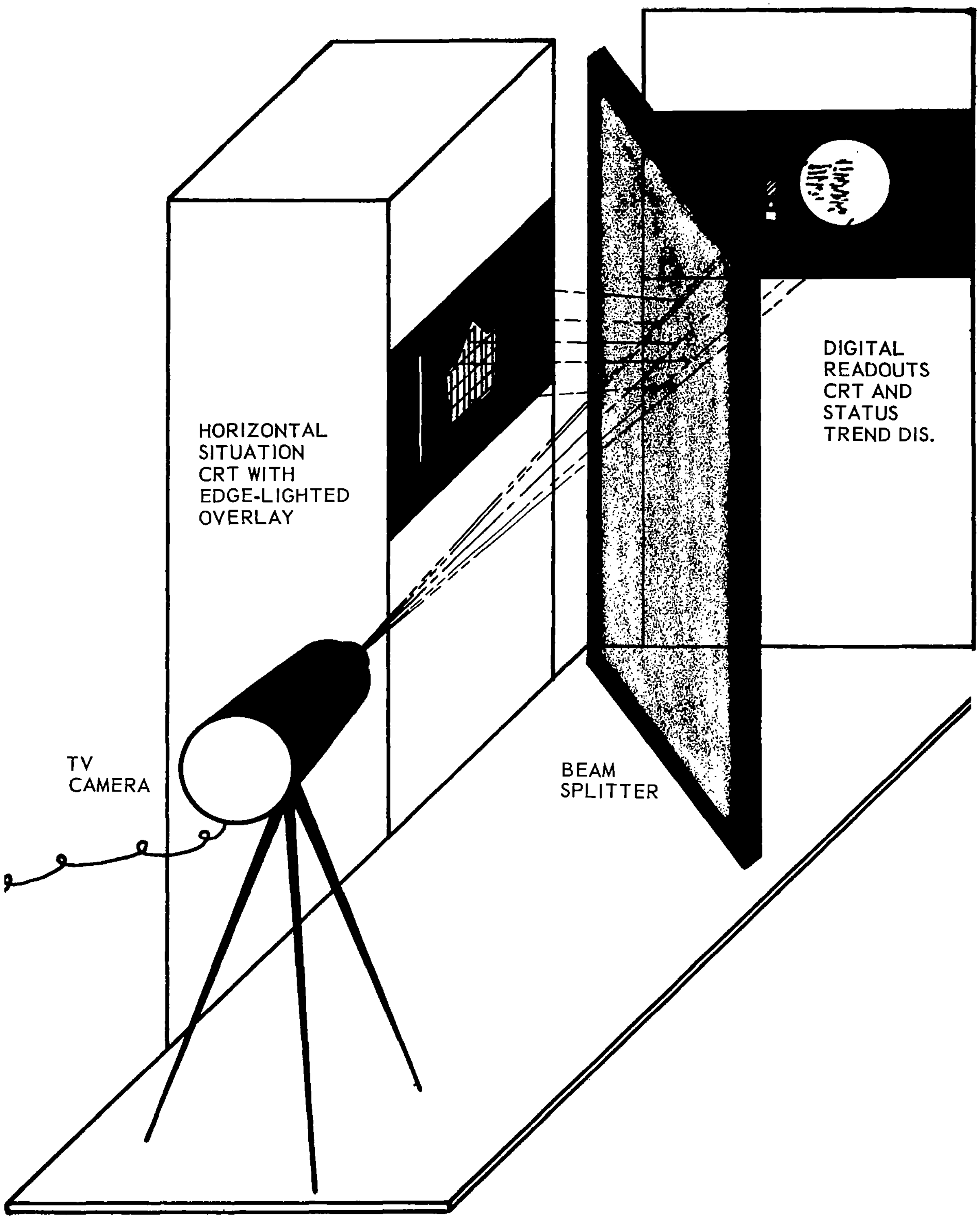


FIGURE 11 HORIZONTAL DISPLAY TV PICKUP ARRANGEMENT

(a) Status-Trend - The Status-Trend display utilized an Industrial Electronics Engineers, Inc. Series 360 Readout Display, a rear projection device incorporating transparencies for twelve different system status conditions. The status conditions were presented individually, in a random order by the computer program. This display appeared on the TV screen when selected by the pilot (self-paced) as part of the task loading portion of the simulation. (See Display Item H for operation.)

(b) Horizontal Situation - The horizontal situation display presented vehicle position and flight path heading information which were generated on a CRT. These were superimposed on a fixed position map and grid background produced by an edge-lighted overlay on the CRT.

The horizontal situation display mode presented was dependent upon the vertical pathway display mode selected. In both the ATTITUDE and COMMAND ATTITUDE display modes the CRT generation presented a straight line along the tube vertical, fore-aft, centerline, which represented the nominal path (required orbital path).

A second straight line depicted present vehicle position and flight path heading. This line was generated in such a fashion that the point at the end which corresponded to present position was heavily accented and the other end pointed in the present direction of flight.

In the COMMAND ATTITUDE mode three additional lines were displayed. Two of these, normal to the nominal path line, designated the longitudinal positions for thrust initiation and termination. The positions of these two markers were pre-set constants for each simulation run. A third line to depict required (commanded) flight path heading was generated in the same manner as the present heading line with the large, heavily accented, end coinciding with that of the present heading line, at the present position of the vehicle. The length of the required heading line was 25 per cent greater than that for the present heading line.

All of the CRT generated lines were produced by a single beam in conjunction with a function stepping switch. In this manner, normal CRT drift characteristics affected all of the lines similarly without changing their relative relationships.

(c) Digital Readouts - The digital readouts were produced by a character generator writing the specified quantities on a second CRT. The displayed parameters varied with display mode. For both modes, the digital readouts included time to event (the event being thrust initiation until it occurred and thereafter, thrust termination) and vehicle velocity values; present (P), required (R), and change (C).

In the COMMAND ATTITUDE mode the attitude angles relating vehicle orientation to the nominal path and local horizontal, for a yaw-pitch-roll Euler convention, were also displayed - the displayed parameters being the present, required, and change values for yaw, pitch, and roll.

(3) Vehicle Thrust Control

A fore-aft, push-pull type control, for left hand operation was provided for primary control of engine thrust. This controller can be seen in the lower left center of Figures 6 and 7. For this simulation only on-off thrust control was utilized, the control being rigged for thrust ON at control positions forward of 25 per cent throw, and thrust OFF for positions aft of that. The microswitch on the control was wired in such a manner as to require both the thrust controller function and nuclear propulsion power switches to be selected before thrust could be obtained.

(4) Vehicle Attitude Controller

A three-axis side arm controller was provided for manual, right-hand, control of attitude about all three vehicle axes - yaw, pitch, and roll. This controller, an LTV development, is part of the right armrest as shown in Figure 12. It is configured so that the yaw and pitch pivots coincided with the wrist pivot of the pilot and the roll axis with his forearm axis through the wrist pivot. With this configuration manual control is possible under high vehicle acceleration. The controller is equipped with spring centering and a positive neutral detent, with full throw displacement of ± 10 degrees, in each of the three axes. In addition, two thumb control trim knobs, pitch and yaw are provided on the hand grip. The function of the side controller varied with attitude control mode, Rate or Acceleration Command.

(a) Rate Command - In the RATE command mode, displacements of the stick in each axis beyond 10% (± 1 degree) of full throw produced angular rate commands proportional to stick displacement - zero at ± 10% up to ± 10 degrees, per second at full throw. The pitch and yaw trim knobs functioned only in the RATE command mode and provided bias signals, rate commands up to about ± 1.5 degrees per second proportional to knob displacement, for such purposes as compensating for engine misalignment moments about each of these axes without having to continually deflect the attitude control.

(b) Acceleration Command - In the ACCELERATION command mode the attitude controller provided direct control of the attitude reaction control jets, commanding the jets on at the maximum acceleration level, ± 5 degrees per second, in the appropriate direction for corresponding control displacements greater than 25 per cent of full throw; and jets off, no acceleration, for lesser displacements.

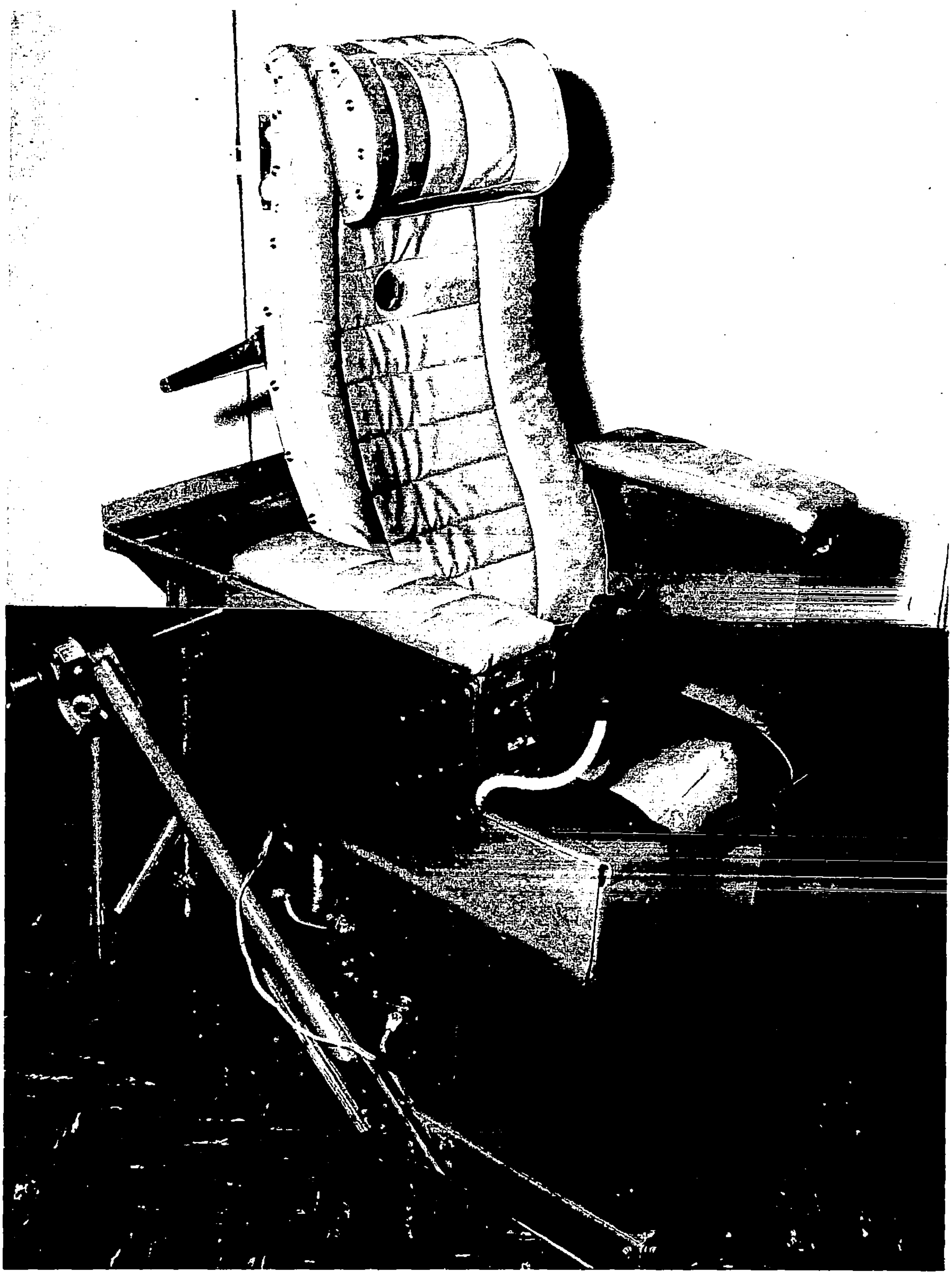


FIGURE 12 CREW STATION SEAT AND VEHICLE ATTITUDE CONTROLLER

(5) RATE/ACCELERATION Attitude Control Function Switch

This alternate action pushbutton switch permitted selection of the attitude control mode, rate or acceleration command. The selected mode was indicated by illuminating the RATE (Top and white illuminated) or ACCELERATION (bottom and blue illuminated) halves of the switch display screen.

(6) NUCLEAR PROPULSION Power Switch

Arming of the nuclear propulsion system prior to thrusting was obtained by this alternate action switch, the display screen of the switch being illuminated (white) when the system was armed.

(7) THRUST Controller Function Switch

This alternate action switch was provided for selecting and arming the vehicle thrust function for the left controller and for a visual indication of propulsion system operation, thrust on. Arming of the vehicle thrust control was indicated by a dimly lit (white) switch display screen, lighting only one of the four indicator lamps, the remaining three lamps being illuminated to produce a brighter (green) display screen when thrust was on. To provide greater flexibility in the simulation the thrust control microswitch and thrust controller function switch interlock was so arranged that the single lamps used for indicating thrust control armed would be lighted whenever either switch was actuated. Thrust could therefore be initiated (providing the nuclear propulsion system was armed) whenever both were actuated, regardless of sequence. This arrangement provided a means for possible evaluation of a pushbutton switch for on-off thrust control in comparison with the linear motion control.

(8) START and STOP PROGRAM Switches

START PROGRAM (computer to operate) and STOP PROGRAM (computer to reset), of the simulation runs was commanded by these two holding coil switches with the appropriate switch display screens being illuminated (white) to indicate the start or stop program condition. The two switches were electrically interlocked such that actuation of either would release the holding coil of the other, thereby deactivating it.

(9) VERTICAL and HORIZONTAL PRESENTATION Switches

These two alternate action switches were used to provide on-off control of the vertical and horizontal displays with the display screen of each switch being illuminated (white) when selected.

(10) Display Mode Switches

Mode selection for both the vertical and horizontal displays was accomplished by means of the ATTITUDE and COMMAND ATTITUDE switches in the vertical display switch group.

These holding coil switches were interlocked with each other such that actuation of one would deactivate the other. They were also interlocked with the VERTICAL and HORIZONTAL PRESENTATION switches such that the mode selection switches were non-functional unless either one of the presentation switches was on. The display screen in each of these switches in the vertical group was illuminated (white) to indicated the selected display mode. In addition, the same display mode in the horizontal display switch group illuminated (white) though the horizontal display switches were non-functional in this simulation for simplicity in simulation setup.

(11) Task Loading Switches

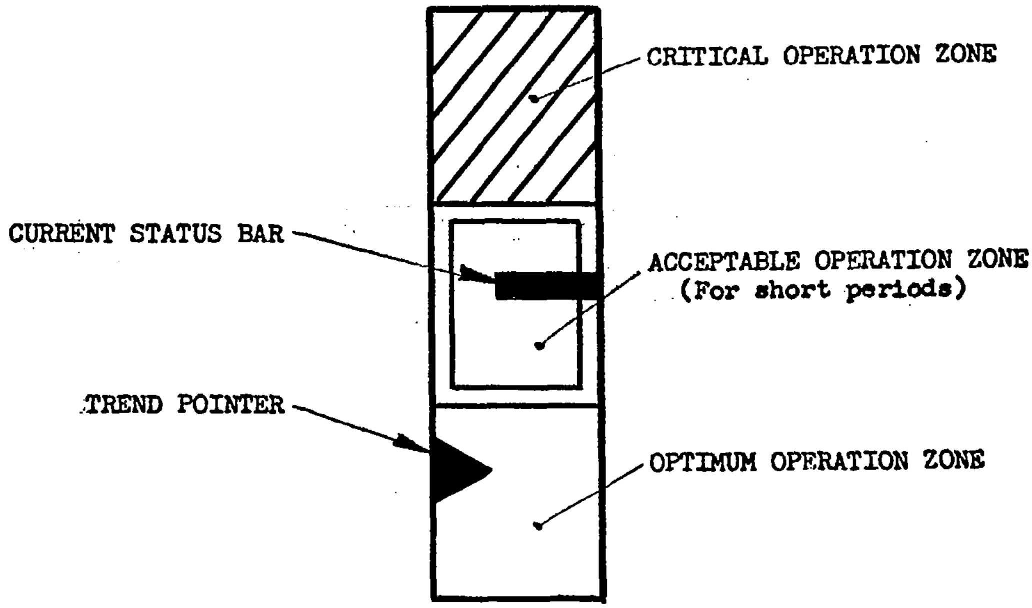
Ten pushbutton switches were implemented for the task loading portion of the simulation - seven holding coil switches and three momentary action switches. Manual operation of these switches was interconnected with a computer logic program to provide a vehicle systems task loading to the pilot on both an operator query and automatic warning basis.

(a) Operator Query - For operator query, functional only when no automatic warning indication existed, the pilot could actuate the SYSTEM OPERATION switch, then select one of five systems by actuating the appropriate switch, and then actuate the STATUS-TREND switch to obtain the system status-trend display on the horizontal TV presentation. Each of these seven switches contained a holding coil interlocked with the computer logic and stayed on and illuminated (white) subsequent to actuation and until the pilot responded properly to the displayed status-trend.

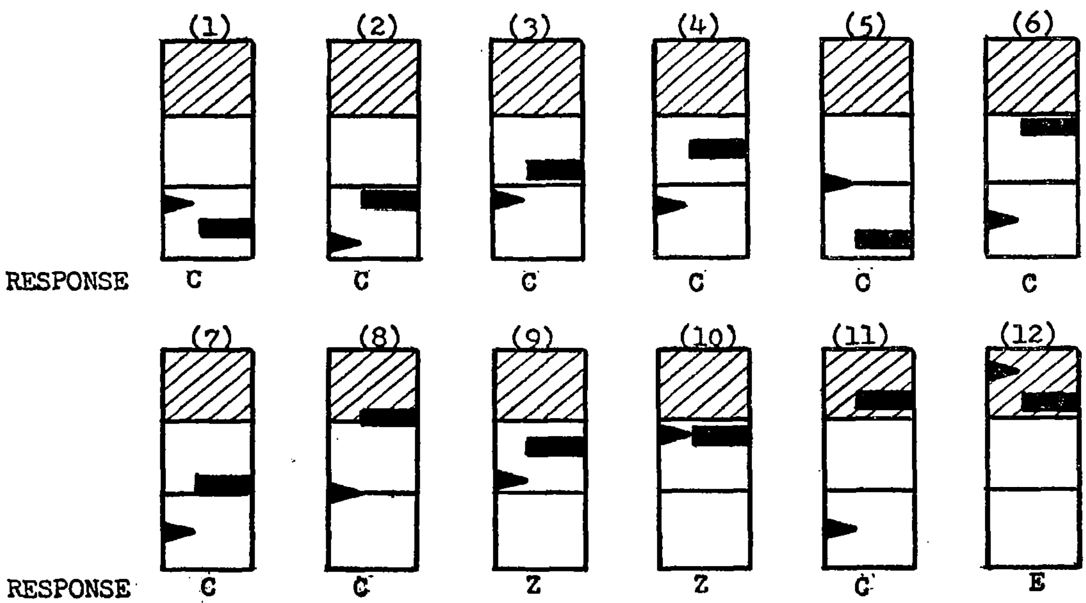
The five functional system switches were ENVIRONMENT, COMMUNICATION, POWER, GUIDANCE AND NAVIGATION, and NUCLEAR PROPULSION.

In conjunction with the particular status-trend which was displayed (twelve different combinations being programmed by the computer on a random basis) there were three possible response actions (only one being correct) which the pilot could make. (Figure 13) These were the actuation of one of three momentary switches; ZERO, CAUTION (in effect extinguishing the original alerting signal) and ESCAPE. Incorrect actions by the pilot produced no results other than for a data record. A correct action resulted in satisfying the computer logic with resultant clearing (turning off) of all associated switches and the status-trend display. An exception occurred when escape was the correct response, actuation of that switch resulted in illuminating (red) the ESCAPE switch display screen and halting the computer.

(b) Automatic Alert - Automatic warnings were indicated by the illumination (amber) of the CAUTION switch and half of the lamps in the associated system switch by the computer program. For these cases the procedure followed by the pilot was similar to that used for an operator query except that it was not necessary to actuate the SYSTEM OPERATION switch, his first action



STATUS-TREND DISPLAY
(Full Size)



STATUS-TREND PRESENTATIONS

Code For Correct Response:

C - Cancel Caution Light   Z - Press ZERO   E - Press ESCAPE, after lifting safety guard.

FIGURE 13 SYSTEM STATUS-TREND DISPLAY

being to actuate the switch for that system associated with the warning. Actuation of the system switch resulted in the illumination of the remaining lamps (white) for its display screen. Subsequent pilot actions were the same as for an operator query.

(12) Miscellaneous Switches

Three other switches were utilized in the crew station panel as indicators only (nonfunctional switches). These were the COMPUTER POWER, CISPLANETARY INJECTION and EARTH COMMUNICATIONS switches which were illuminated (white) at all times when 28 VDC power was supplied to the gondola.

2.3.3 Master Control Station

The simulator operations were directed from the master control station, Figure 14. Included in this station were a control console, the Norden vertical display generator console, and the data recording equipment. The control console contained the intercom system controls; a repeater display for the horizontal presentation; indicator lights for display mode, attitude mode, and engine on-off; and a number of simulation control switches. The Norden display generator console included a repeater display of the vertical presentation.

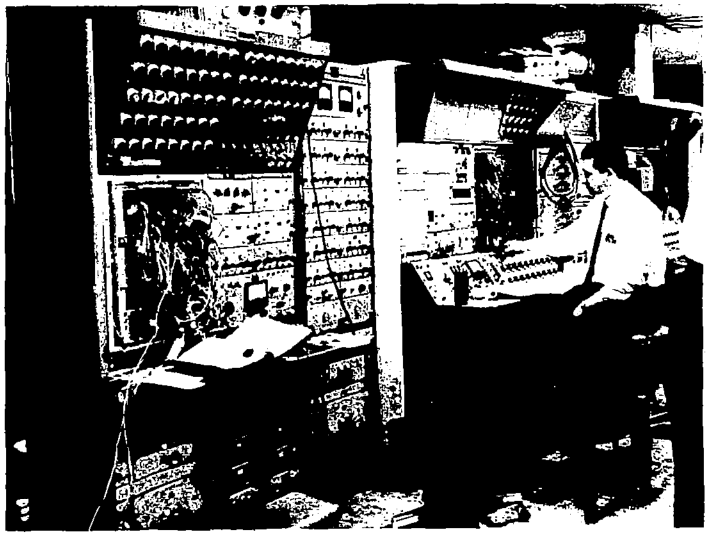
2.3.4 Hybrid Computation Setup

The hybrid, analog-digital computer arrangement, part of the LTV Simulation and Analog Computation Facility, is shown in Figure 14. The primary computing tasks for the simulation were performed with an ASI-2100 digital computer with associated analog-to-digital and digital-to-analog conversion. Analog computing equipment was utilized where necessary to supply such functions as display and moving base drive signals. A schematic of the computer arrangement is shown in Figure 15.

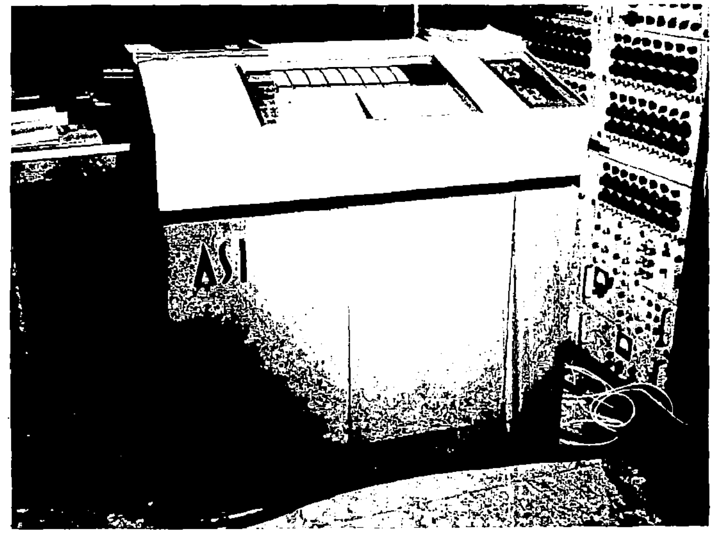
2.3.4.1 Data Recording

Recording of the required data was accomplished with a digital line printer; a dual pen 30 x 30 inch plotter; and two six channel strip chart recorders. The 30 x 30 inch plotter was used to record a three-dimensional trajectory plot. One pen plotted the projection of the trajectory into the nominal orbital plane, Xp vs Zp, where Xp coincided with the local radius vector at the nominal insertion, thrust termination, point. The other pen recorded the out-of-plane plot, Xp vs Zp, Yp being normal to the nominal orbital plane. A typical plot is shown in Figure 16.

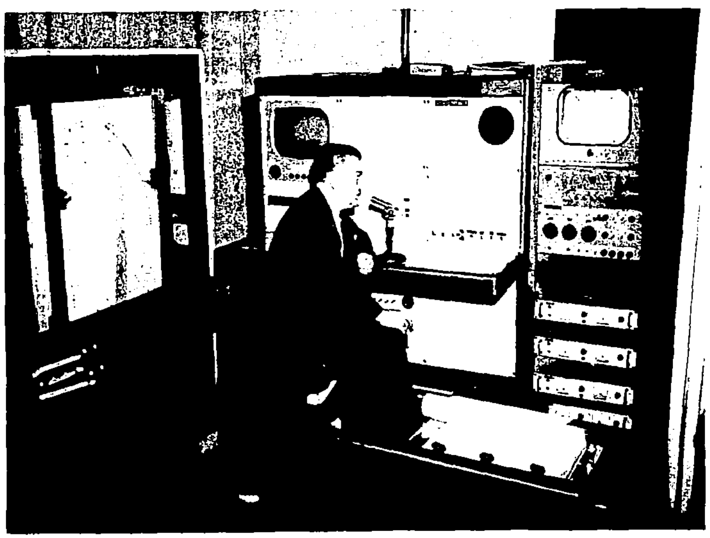
The strip chart recorders were used to record time histories of: attitude controller deflections in pitch, roll, and yaw; trim knob displacement in pitch, roll, and yaw; task loading response times; and engine thrust initiation and termination. Examples of recorded data are shown in Figure 17.



ANALOG EQUIPMENT



ASI LINE DATA PRINTER



CONTROL STATION

ASI–2100 DIGITAL COMPUTER

FIGURE 14 COMPUTER AREA

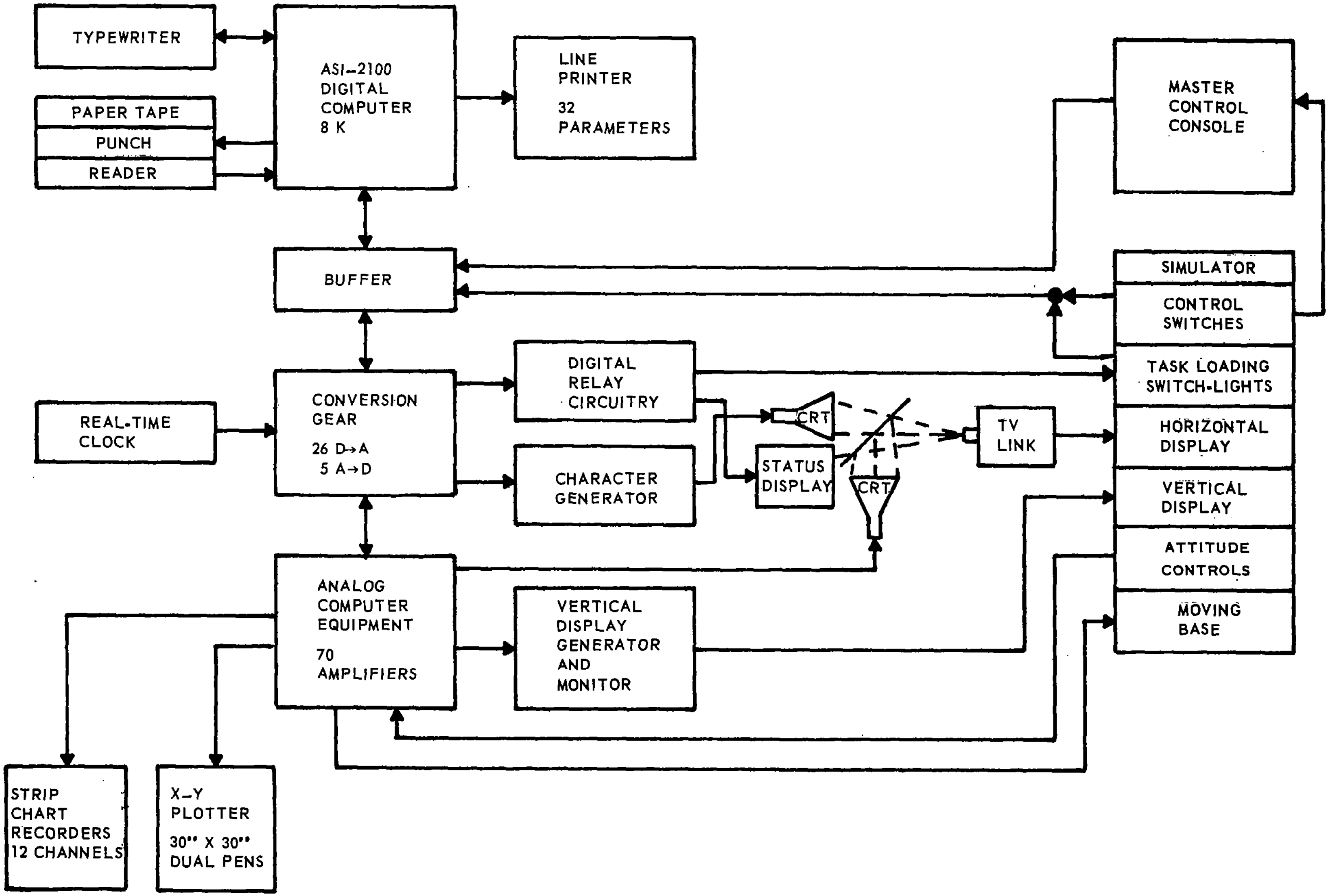


FIGURE 15 SIMULATION EQUIPMENT SCHEMATIC

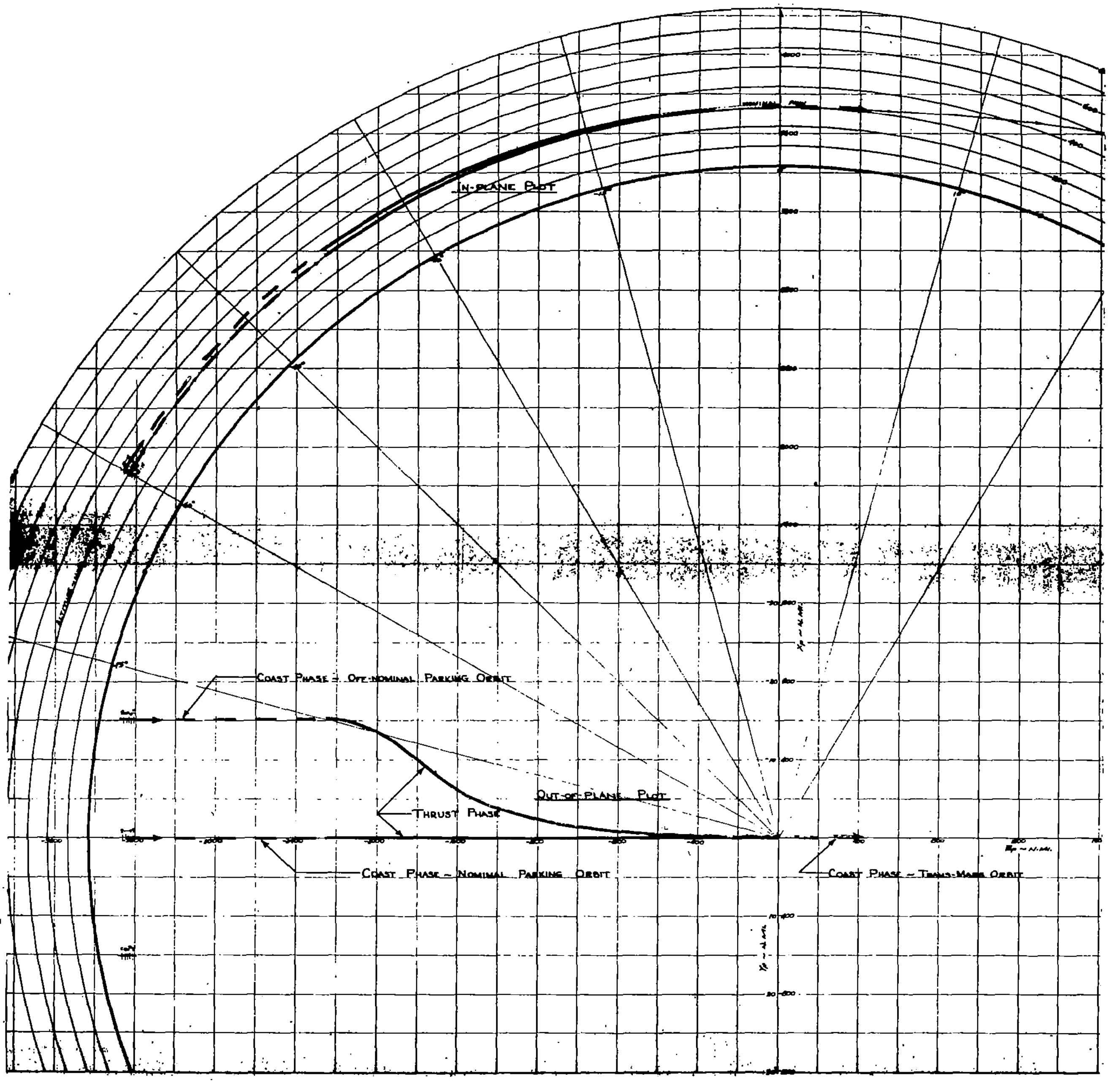
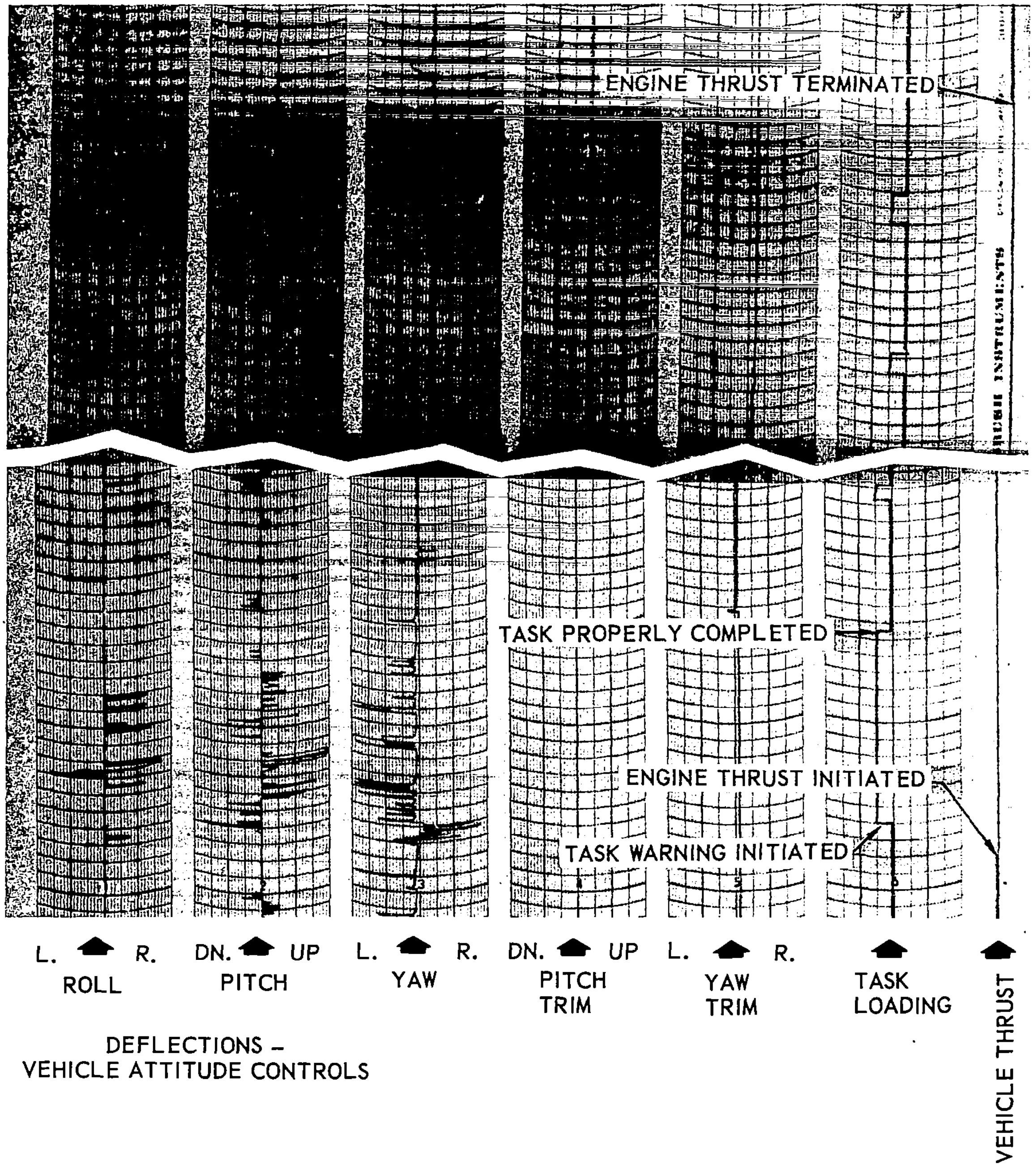


FIGURE 16 THREE DIMENSIONAL TRAJECTORY PLOT



1. CHART MOTION – (1) MILLIMETER PER SECOND
2. FOR RECORDS (1) THROUGH (5), CHART WIDTH REPRESENTS FULL DEFLECTION RANGE FOR APPLICABLE CONTROL.

FIGURE 17 TYPICAL DATA RECORDS FOR CONTROL POSITIONS AND TASK LOADING

The digital line printer recorded 32 parameters on a time or function command basis. Time based printouts were obtained at one minute intervals during nonthrusting flight and at 20 second intervals while thrusting. In addition, function commanded printouts occurred at engine ignition and termination and with computer reset, stop program. Printouts could also be manually commanded from the master control console. Format used is shown in Figure 18.

Further details on recorded data are given in Section 2.5.2 Measurements.

NOTE: TERM "E–(NO.)" PLACES DECIMAL POINT. EXAMPLE – 077849 E–2 = 0778.49

TME	077849 E-2	403346 E-1	182259 E-0	-000002 E-3	-000008 E-3	-003439 E-3	000000 E-3	062241 E-3
	000011 E-0	-003697 E-3	-044939 E-3	004222 E-3	000000 E-3	000000 E-3	000831 E-3	-044835 E-3
	-004528 E-3	-000105 E-3	004528 E-3	000105 E-3	009007 E-3	004073 E-3	004052 E-3	184653 E-1
	018342 E-2	115152 E-2	103831 E-2	016664 E-1	000002 E-3	-000220 E-0	-012937 E-4	008706 E-4
TME	079849 E-2	412184 E-1	182253 E-0	000000 E-3	-000038 E-3	-001405 E-3	-000001 E-3	065133 E-3
	000011 E-0	-000734 E-3	-046119 E-3	000957 E-3	000000 E-3	000000 E-3	004075 E-3	-046312 E-3
	-004809 E-3	000195 E-3	004809 E-3	-000195 E-3	008785 E-3	003933 E-3	003959 E-3	197384 E-1
	018367 E-2	120570 E-2	106109 E-2	007816 E-1	000000 E-3	-000260 E-0	-013745 E-4	009110 E-4
SEN	081789 E-2	420787 E-1	182249 E-0	000001 E-3	000079 E-3	000607 E-3	-000002 E-3	068200 E-3
	000011 E-0	013526 E-3	-049246 E-3	-007268 E-3	000000 E-3	000000 E-3	-005479 E-3	-047503 E-3
	019005 E-3	-001742 E-3	-019005 E-3	001742 E-3	008761 E-3	003823 E-3	003993 E-3	210277 E-1
	019375 E-2	124032 E-2	109645 E-2	-000788 E-1	-000001 E-3	-000316 E-0	000000 E-4	000000 E-4
EPT	083029 E-2	420761 E-1	182636 E-0	000846 E-3	000079 E-3	001907 E-3	000000 E-3	068200 E-3
	000011 E-0	016159 E-3	-051867 E-3	-009039 E-3	000000 E-3	000000 E-3	-006689 E-3	-057296 E-3
	022848 E-3	005427 E-3	-022848 E-3	-005427 E-3	008761 E-3	003823 E-3	003993 E-3	210277 E-1
	019412 E-2	124069 E-2	110939 E-2	-000761 E-1	-000846 E-3	003573 E-0	000000 E-4	000000 E-4

ASI 2100 LINE PRINTER DATA (TYPICAL)

EVENT								
TME – TIME FEN – FIRE ENGINE SEN – SHUTOFF ENGINE EPT – END POINT MAN – MANUALLY SELECTED PRINTOUT	1. ELAPSED TIME t (SEC.)	2. ORBITAL VELOCITY ν (FT.)	3. ALTITUDE h/10 (FT.)	4. ACTUAL FLIGHT PATH ELEVATION γ (DEG.)	5. FLIGHT PATH HEADING ψ_H (DEG.)	6. ORBITAL LONGITUDE Y_{RP} (DEG.)	7. ORBITAL LATITUDE Z_{RD} (DEG.)	8. THRUST/MASS RATIO T/M
	9. & 10. CONTROL MODE AND DISPLAY MODE	11. PRESENT YAW ψ_3 (DEG.)	12. PRESENT PITCH θ_3 (DEG.)	13. PRESENT ROLL ϕ_3 (DEG.)	14. & 15.* YAW RATE COMMAND $\dot{\psi}_C$ (DEG/SEC) REFERENCE PITCH ANGLE θ_{REF} (DEG.)	16. & 17.* PITCH RATE COMMAND $\dot{\theta}_C$ (DEG/SEC) VELOCITY ERROR E (FPS)	18. YAW COMMAND ψ_C (DEG.)	19. PITCH COMMAND θ_C (DEG.)
	20. YAW ERROR TERM ψ_ϵ (DEG.)	21. PITCH ERROR TERM θ_ϵ (DEG.)	22. YAW CORRECTION $-\epsilon\psi$ (DEG.)	23. PITCH CORRECTION $-\epsilon\theta$ (DEG.)	24. INTEGRATED ABSOLUTE ERROR YAW $\xi\psi_{ABS}$ (DEG.)	25. INTEGRATED ABSOLUTE ERROR PITCH $\xi\theta_{ABS}$ (DEG.)	26. INTEGRATED ABSOLUTE ERROR ROLL $\xi\phi_{ABS}$ (DEG.)	27. VELOCITY CHANGE ΔV (FPS)
	28. ENERGY EXPENDED ROLL ΔP_s (DEG/SEC)	29. ENERGY EXPENDED PITCH Δq_s (DEG/SEC)	30. ENERGY EXPENDED YAW Δr_s (DEG/SEC)	31. VELOCITY ERROR $-\epsilon_V$ (FPS)	32. FLIGHT PATH ELEVATION ERROR $-\epsilon_\gamma$ (DEG)	33. ALTITUDE ERROR RELATIVE TO NOMINAL Δh (FT)	34. PITCH ACCELERATION $\Delta\dot{q}_E$ (DEG/SEC^2)	35. YAW ACCELERATION $\Delta\dot{r}_E$ (DEG/SEC^2)

*UPPER TERM PRESENTED BEFORE PM OF 2/2/66; LOWER TERM THEREAFTER.

SEE TABLE 5 FOR FURTHER DEFINITIONS.

PRINTOUT IDENTIFICATION

FIGURE 18 DIGITAL PRINTOUT FORMAT – FIRST EVALUATION

2.4 SUBJECTS

Twelve prospective subjects, LTV engineers and Navy BuWeps personnel, were contacted on the basis of their known pilot experience. It was important in this study, because of the limited two week experimental period, to have as homogeneous a pilot population as possible.

Subjects were selected according to the following criteria:

2.4.1 Qualifications

(a) Over 1000 hours jet aircraft experience (either single or multiple engine).

(b) Over ten years total aircraft experience.

(c) Over 1500 total flight hours.

These criteria were established on the basis of the preliminary questionnaire sent prospective pilot candidates.

2.4.2 Selection and Grouping

It was possible to select a very homogeneous group of six subjects. Of the six, four were LTV engineers who were currently active in military reserve flight programs, and two were engineering flight test personnel assigned to the LTV Navy BuWeps Representative Office and commissioned officers in the U. S. Navy.

Table 2 lists pertinent data on these pilots. The numbers appearing in this table are used for pilot identification in the remainder of this report.

TABLE 2

SIMULATION PILOTS EXPERIENCE AND QUALIFICATIONS

Pilot	Age	Total Years Flight Experience	Total Jet Hours	Total Flight Hours
1	35	15.5	1500	2500
2	37	13.0	2000	2700
3	36	14.5	1600	2800
4	36	13.0	1000	1800
5	36	20.0	1900	2200
6	36	13.5	1700	3400
Means	36	14.9	1618	2567

Pilots 1, 2, and 3, were assigned to Group I (display gain of 1.75:1). Pilots 4, 5, and 6, were assigned to Group II (variable display gain of 8.75:1 max.), with Subjects 5 and 6 performing their final block of flights with a gain of 1:1. It should be noted that the assignment of subjects to groups was a random process, the enumeration of subjects taking place after group assignment and scheduling.

Within Group I, Pilots 2 and 3 were provided digital information on the Horizontal Display; Subject 1 had analog information only. Within Group II, Pilots 4 and 5, had analog information only, Pilot 6 had digital information as well. This subject assignment to groups is summarized in Table 3.

TABLE 3

SUBJECTS GROUP ASSIGNMENTS

	DISPLAY GAIN*	
	I (1.75:1)	Variable to II (8.75:1 Max.)
ANALOG ONLY	Pilot 1	Pilot 4 Pilot 5**
ANALOG AND DIGITAL	Pilot 2 Pilot 3	Pilot 6**

*See Section 2.5.1.1 **Final block of runs with a gain of 1:1

2.4.3 Evaluative Subjects

A number of engineering shakedown flights were made prior to the beginning of the formal experimental test period by the MAFS Group Supervisor. These flights are documented in the Flight Log, and were conducted to establish the combinations of variables to be used with the simulation subjects. Experience and qualifications of the MAFS Supervisor were equal or superior to those of the test population.

In addition, a certain number of speculative runs were made after the experimental period by the program Simulation Engineer, in preparation for the Second Evaluation.

2.5 PROCEDURE

2.5.1 Independent Variables

The First Evaluation is classed as a "Feasibility Demonstration" in which the principal objective is to show whether or not management of a given maneuver or mission is possible under the control and display setup used (Reference 6). The initial program plan for the First Evaluation (Reference 7) identified such independent (or experimental) variables as the presence or absence of digital readouts and use of acceleration vs. rate command in attitude control. Somewhat later in the program (January 1965) it was determined that display gain was a worthwhile variable to investigate. The Display System Demonstrator provided by Norden Division of United Aircraft had total errors in attitude command of one to three degrees, but the attitude profile had to be controlled to less than one degree error to provide an adequate insertion into cisplanetary orbit. Thus the ability of the available means of display of commanded attitude was marginal as far as control accuracy was involved and it was further considered that such display errors were not unreasonable in an operational space vehicle attitude display. It was thereupon decided to incorporate gain change capability in the simulation.

2.5.1.1 Gain Variable

Three types of gain were set up initially: (the gain was identical for pitch, roll, yaw)

(1) GAIN 1.75:1: This was to be no gain change (or 1:1), but an inadvertent miswrite of computation program resulted in a constant gain of 1.75 to one, i.e., an error of 1 degree appeared on the display as an error of 1.75 degrees.

(2) STEP GAIN: This was a step change in gain at attitude errors below 1 degree from 1:1 to 5:1. This change was superimposed over the 1:75 to 1 basic gain of the vertical display setup, so the gain was actually 8.75 to 1.

(3) VARIABLE GAIN: This was a linear gain change from 1.75:1 at 2 degrees error to 8.75:1 at 0.1 degree error. Gain was a constant 8.75:1 from 0.1 degree error to zero error.

The implementation of these gain schemes is explained in Appendix I-A. From an operational standpoint, Step Gain was perceived by the pilot as a sudden increase in sensitivity of the vehicle to corrective attitude control system inputs when the displayed attitude error was nearly nullified. Variable gain was perceived as a gradual increase in such sensitivity. Both gain change methods produced an attitude command display resembling a quickened display of error, though, the implementation was entirely different.

During the last week of experimental runs the programming error which resulted in the overall 1.75:1 gain was discovered. It was decided, therefore, to test the last two pilots, 5 and 6, on a rectified 1:1 gain on their last experimental day. Thus GAIN (1:1) was the fourth, if belated, level of the GAIN independent variables.

2.5.1.2 Digital Information Variable

The other principal experimental variable in the First Evaluation was the presence or absence of digital information as backup to the analog presentations of the vertical and horizontal displays. The following parameters of information were presented in digital form on the Horizontal Display: (Figure 10).

(1) TIME TO EVENT: In minutes and seconds.

(2) VELOCITY: PRESENT - (P), in feet per second
REQUIRED- (R), in feet per second
CHANGE - (C), difference between (P) and (R) in feet per second.

(3) PITCH: PRESENT - (P), up (U) or down (D) in degrees and tenths
REQUIRED - (R), up (U) or down (D) in degrees and tenths
CHANGE - (C), difference between (P) and (R) in degrees and tenths

(4) ROLL: PRESENT - (P), left (L) or right (R) in degrees and tenths
REQUIRED - (R), left (L) or right (R) in degrees and tenths
CHANGE - (C), difference between (P) and (R) in degrees and tenths

(5) YAW: PRESENT - (P), left (L) or right (R) in degrees and tenths
REQUIRED -(R), left (L) or right (R) in degrees and tenths
CHANGE -(C), difference between (P) and (R) in degrees and tenths

Only the first two parameters appeared in ATTITUDE Mode; all appeared when the pilot selected COMMAND ATTITUDE Mode.

The digital information was generated with a character generator on a cathode ray tube (CRT), as explained in Appendix I-A, which image was then transmitted by closed-circuit TV to the horizontal display. The clarity of the digital display was inferior because of CRT difficulties and interfered with effective use of the information when used.

2.5.1.3 Attitude Control Mode Variable

The original experimental program plan called for comparison of two types of attitude control systems.

The first type being ACCELERATION command in which actuation of the attitude controller produced a constant angular acceleration about the axis commanded. The longer the control was held on, the faster the angular rate attained. The rotation imparted to the vehicle was cancelled by opposite deflection of the control for an equal period of time.

The second type of control was RATE command, in which angular rate of rotation of the vehicle about any axis was proportional to the amount of attitude controller deflection. Release of the control automatically damped the induced rate. Operational capabilities of the control modes are described in Section 2.3.2, while implementation of the control system is described in Appendix I-A, Section 2.2.

In a series of preliminary shake down flights, which were documented in the Flight Log, both types of attitude command were evaluated. It was quickly determined that the vehicle was virtually unmanageable when in ACCELERATION command. Angular rates achieved, quickly reached the limit of scaling in the ASI 2100 digital computer, which thereupon halted. The subject felt that the mode "could be learned", but not without considerable practice time. The fact that the ACCELERATION command mode is considered to be an emergency form of control coupled with the stringent time limitations of the First Evaluation, caused the deletion of ACCELERATION command from further consideration in the study. All subsequent flights were made with RATE command.

In the same set of preliminary flights, the various gain-change methods were investigated, and Step Gain was also eliminated. The sudden increase in sensitivity of the error signal to the command path was considered to be very disruptive, and to have no advantages over Variable Gain. It was thus decided to study only two gain change conditions: Gain 1.75:1 and Variable Gain.

2.5.1.4 Initial Conditions

A set of fifteen initial flight conditions were set up for this study. The pilot would find himself in any one of these fifteen conditions when he initiated a flight by pushing START PROGRAM. The vehicle could be in the nominal plane, or out-of-plane to the left or to the right. The vehicle could be at the nominal altitude (300 nautical miles) or above or below this altitude. It could be in a circular or elliptical orbit, and if in an elliptic, be on the ascending or descending side of the apogee. Additionally, each initial condition was accompanied by an initial attitude, each being a random combinations of pitch, roll and yaw. Table 4 lists these initial positional conditions and a description of each from the standpoint of the subject. Conditions 1, 2, and 3 were presented on the first, or familiarization day. On succeeding experimental days, all conditions except 1, the on-nominal-path condition, were presented.

2.5.2 Measurements

Principal performance data were obtained through the ASI Digital Line Data Printer. This device printed out pertinent system performance data every 60 seconds starting 60 seconds after initiation of each flight and every 20 seconds after ignition. Special printouts occurred at engine ignition and shutoff. These printouts are identified on the data sheets as follows:

TME: Time identification of printout (TiME)
FEN: Printout at moment of engine ignition (Fire ENgine)
SEN: Printout at moment of engine shutoff (Shutoff ENgine)
EPT: Printout at termination of run and computer reset (End PoinT)

NO.	ALTITUDE	PLANE RELATION*	REMARKS
1.	Nominal	In plane	Same as nominal - circular orbit.
2.	Nominal	15.1 miles right of plane	
3.	Nominal	15.1 miles left of plane	
4.	12.5 miles below	In plane	Elliptical orbit - climbing toward minor axis.
5.	12.5 miles below	15.1 miles right of plane	
6.	12.5 miles below	15.1 miles left of plane	
7.	12.5 miles above	In plane	Elliptical orbit - descending toward minor axis.
8.	12.5 miles above	15.1 miles right of plane	
9.	12.5 miles above	15.1 miles left of plane	
10.	33.3 miles above	In plane	Elliptical orbit - climbing toward apogee.
11.	33.3 miles above	15.1 miles right of plane	
12.	33.3 miles above	15.1 miles left of plane	
13.	33.3 miles below	In plane	Elliptical orbit - descending toward perigee.
14.	33.3 miles below	15.1 miles right of plane	
15.	33.3 miles below	15.1 miles left of plane	

*With respect to Nominal

TABLE 4 - INITIAL VEHICLE CONDITIONS

The data reported in this document are derived from EPT or SEN denoted printouts.

The system performance measurements processed through the digital computer are listed and defined in Table 5, while Figure 18 describes the printout format.

In addition to digital printout information, several analog channels in the simulation were recorded for reference on a Brush Oscillograph as follows:

(1) Controller deflection--pitch
(2) Controller deflection--roll
(3) Controller deflection--yaw
(4) Trim knob displacement--pitch
(5) Trim knob displacement--yaw
(6) Task loading response times
(7) Engine Thrust, On-Off

These data were not reduced during the First Evaluation.

It was planned to use an X-Y plotter to record the flight path trace during each run, but in practice it was found that the resulting plots were not sufficiently informative to justify further data recording with the plotter. It was thereafter used as a flight progress display by the Test Conductor. A typical flight is presented in Figure 16.

2.5.3 Pilot Questionnaire

All simulation pilots were given a short questionnaire to answer upon completion of their flights in the simulator. The questionnaire was similar to the form used for pilot reports on test aircraft. A few of the items on the form were short-answer, but most were rating questions, i.e., a particular feature of the cockpit was to be graded on a three-point scale. Generally, an approving or positive rating was to be "3", a neutral reaction "2", and an unfavorable grade "1". The questionnaire with pilot responses is enclosed as Appendix I-B .

Pilots comments made in the course of experimental runs or at other times were recorded in the Simulation Flight Log which is described in Section 2.5.6.

2.5.4 Pretraining

All six pilots were interviewed, ten days before the start of the experimental runs, for final acceptance as subjects. At that time, a specially prepared Pilot Handbook (Reference 8) was given to them for study. Contents of the Pilot Handbook included:

(1) Introductory information on the program.

(2) Simulated vehicle characteristics, a description of the vehicle's propulsion and reaction control systems, the two modes of attitude control, and related material.

PARAMETER	SYMBOL	DEFINITION	PERFORMANCE IMPLICATION
1. ELAPSED TIME	t	Time from initiation.	Locates other parameters in time history of flights.
2. ORBITAL VELOCITY	V	Inertial velocity resultant.	
3. ALTITUDE	h	Vehicle height relative to surface of the earth.	Computation term.
4. FLIGHT PATH ELEVATION	γ	Angle between vehicle path and nominal in nominal plane.	Should be zero at injection
5. FLIGHT PATH HEADING	ψ_H	Angle between vehicle path and nominal in local horizontal plane.	Should be zero at injection.
6. ORBITAL LONGITUDE	$\textcircled{Y}_{RP}$	Central angle between vehicle position and nominal position in nominal plane.	At injection, expresses under or overshoot position. Should be zero.
7. ORBITAL LATITUDE	$\textcircled{Z}_{RD}$	Central angle between vehicle position and nominal position in plane normal to nominal.	At injection, expresses out-of-plane position. Should be zero.
8. THRUST-TO-MASS RATIO	T/M	Increasing ratio due to reduction in fuel mass during thrusting period.	Computation term.
9. CONTROL MODE		Status Term: 00000 = Acceleration Mode 00001 = Rate Mode	Single sum term defines both mode selections.
10. DISPLAY MODE		Status Term: 0000 = Attitude 0001 = Command Attitude	
11. PRESENT YAW	ψ_3	Euler angle, relative to local vertical axes.	Computation term.
12. PRESENT PITCH	θ_3	Euler angle, relative to local vertical axes.	Computation term.

TABLE 5 DEFINITION - DIGITAL PRINTOUT PERFORMANCE MEASUREMENTS SHT. 1 of 3
FIRST EVALUATION

PARAMETER	SYMBOL	DEFINITION	PERFORMANCE IMPLICATION
13. PRESENT ROLL	ϕ_3	Euler angle, relative to local vertical axes.	Computation term.
14. YAW RATE COMMAND	$\dot{\psi}_c$	Rate of change of yaw rate command.	Computation term. (Secondary).
15. PITCH REFERENCE	θ_{REF}	Reference pitch angle.	Computation term.
16. PITCH RATE COMMAND	$\dot{\theta}_c$	Rate of change of pitch rate command.	Computation term. (Secondary).
17. VELOCITY ERROR COMPONENT	V_ϵ	Prior to ignition command, $V_\epsilon = 0$, prior to ignition, $V_\epsilon = \epsilon_V$; after ignition, $-\epsilon_V = V_E + .7\ T/M$	Computation term; check quantity.
18. YAW COMMAND	ψ_c	Yaw attitude command.	Ideally, values follow nominal command profile.
19. PITCH COMMAND	θ_c	Pitch attitude command.	Ideally, values follow nominal command profile.
20. YAW ERROR	ψ_ϵ	Yaw error term (path signal).	Value at all times close to zero for optimum performance.
21. PITCH ERROR	θ_ϵ	Pitch error term (path signal).	Value at all times close to zero for optimum performance.
22. YAW CORRECTION	$-\epsilon_\psi$	$\psi_c - \psi_3$	Computation term.
23. PITCH CORRECTION	$-\epsilon_\theta$	$\theta_c - \theta_3$	Computation term.
24. AVERAGE ABSOLUTE ERROR YAW	$\epsilon_{\psi_{ABS}}$	Average yaw error over a time period.	During thrust period, should stay close to zero; a measure of controller accuracy.
25. AVERAGE ABSOLUTE ERROR PITCH	$\epsilon_{\theta_{ABS}}$	Average pitch error over a time period.	During thrust period, should stay close to zero; a measure of controller accuracy.

TABLE 5 DEFINITIONS - DIGITAL PRINTOUT PERFORMANCE MEASUREMENTS SHT. 2 of 3
FIRST EVALUATION

PARAMETER	SYMBOL	DEFINITION	PERFORMANCE IMPLICATION
26. AVERAGE ABSOLUTE ERROR ROLL	$\epsilon_{\phi_{ABS}}$	Average roll error over a time period.	During thrust period, should stay close to zero; a measure of controller accuracy.
27. VELOCITY CHANGE	ΔV	Energy gained from thrust initiation to termination.	$V_{NOM.} - V_{ACTUAL} \rightarrow 0$ for optimum performance.
28. ENERGY - ROLL	Δp_s	Ideal angular velocity expended around roll axis.	Fuel expenditure correlate. Used with average absolute error to establish control usage efficiency.
29. ENERGY-PITCH	Δq_s	Ideal angular velocity expended around pitch axis.	Fuel expenditure correlate. Used with average absolute error to establish control usage efficiency.
30. ENERGY-YAW	Δr_s	Ideal angular velocity expended around yaw axis.	Fuel expenditure correlate. Used with average absolute error to establish control usage efficiency.
31. VELOCITY ERROR	$-\epsilon_V$	Actual velocity versus commanded velocity.	Reflects pitch profile management proficiency plus response to shut-off due.
32. FLIGHT PATH ANGULAR ERROR	$-\epsilon_\gamma$	Difference between actual flight path elevation to local horizontal and required.	Overall pilot performance in pitch profile management.
33. ALTITUDE ERROR RELATIVE TO NOMINAL	Δh	Reference is 300 N. M.	Pitch profile management indicant.
34. PITCH ACCELERATION	$\Delta \dot{q}_E$	Pitch angular acceleration contribution from engine misalignment.	Computation term.
35. YAW ACCELERATION	$\Delta \dot{r}_E$	Yaw angular contribution from engine misalignment.	Computation term.

TABLE 5 - DEFINITIONS - DIGITAL PRINTOUT PERFORMANCE MEASUREMENTS SHT. 3 of 3
FIRST EVALUATION

(3) Flight plan, in which the cisplanetary injection maneuver was described, and the general tasks to be performed were indicated. Also, the display setup was placed in its historical context and described.

(4) Panel Description, a functional item-by-item description of all displays and controls in the cockpit.

(5) Flight management procedures, a task description and check list detailing what was to be done during a simulator run.

(6) System management procedures, a task description of the systems monitoring (task loading) job.

Subjects were encouraged to contact the Program Office if questions arose while they were studying the Pilot Handbook.

All subjects were aware of the fact that some of their number would have digital information and others would not (the task descriptions had branching instructions for both groups). None were aware that gain of the vertical display error presentation was a variable in the study.

The first day for each subject was designated as the Familiarization Day, and is so recorded in the Flight Log. The subject reported for his experimental period at either 8:30 a.m. or 1:00 p.m. The main points in the Pilot Handbook were covered in a short briefing conducted with the mockup of the crew station. (Figures 19 and 20.) The pilot was given a few ground rules for correcting attitude error while in the extreme pitchdown posture which characterized this simulation toward the end of each run. (These will be covered later.) The pilot was then taken to the MAFS and seated in the moving base gondola. There he was briefed on flight procedures by the Simulation Engineer and given safety instructions in case a malfunction occurred while the moving base was connected to the computer facility.

The first one or two flights were conducted in automatic attitude mode. The attitude profile was managed by the computer, the only pilot tasks being to initiate and terminate thrust, and monitor the system status displays. An out-of-plane initial condition was programmed to permit the pilot to observe both the pitch profile and the yaw profile he would be managing. At the same time, he could without much interference, learn to respond appropriately to the systems warning and parameter lights, and read the system Status-Trend presentation on the Horizontal Display.

Following the automatic attitude control runs, the pilot was given manual control. The first three manual runs were conducted with the systems monitoring task disconnected, to enable the pilot to devote full time to flight management. The first four initial conditions were used for these familiarization runs. The pilot was "talked through" his early flights by the Test Conductor. It was emphasized that the subject should not attempt to control more than one axis at a time until he was accustomed to the control characteristics of the vehicle and he was encouraged to explore. It was pointed out that roll should be nulled first, then heading, and finally pitch,

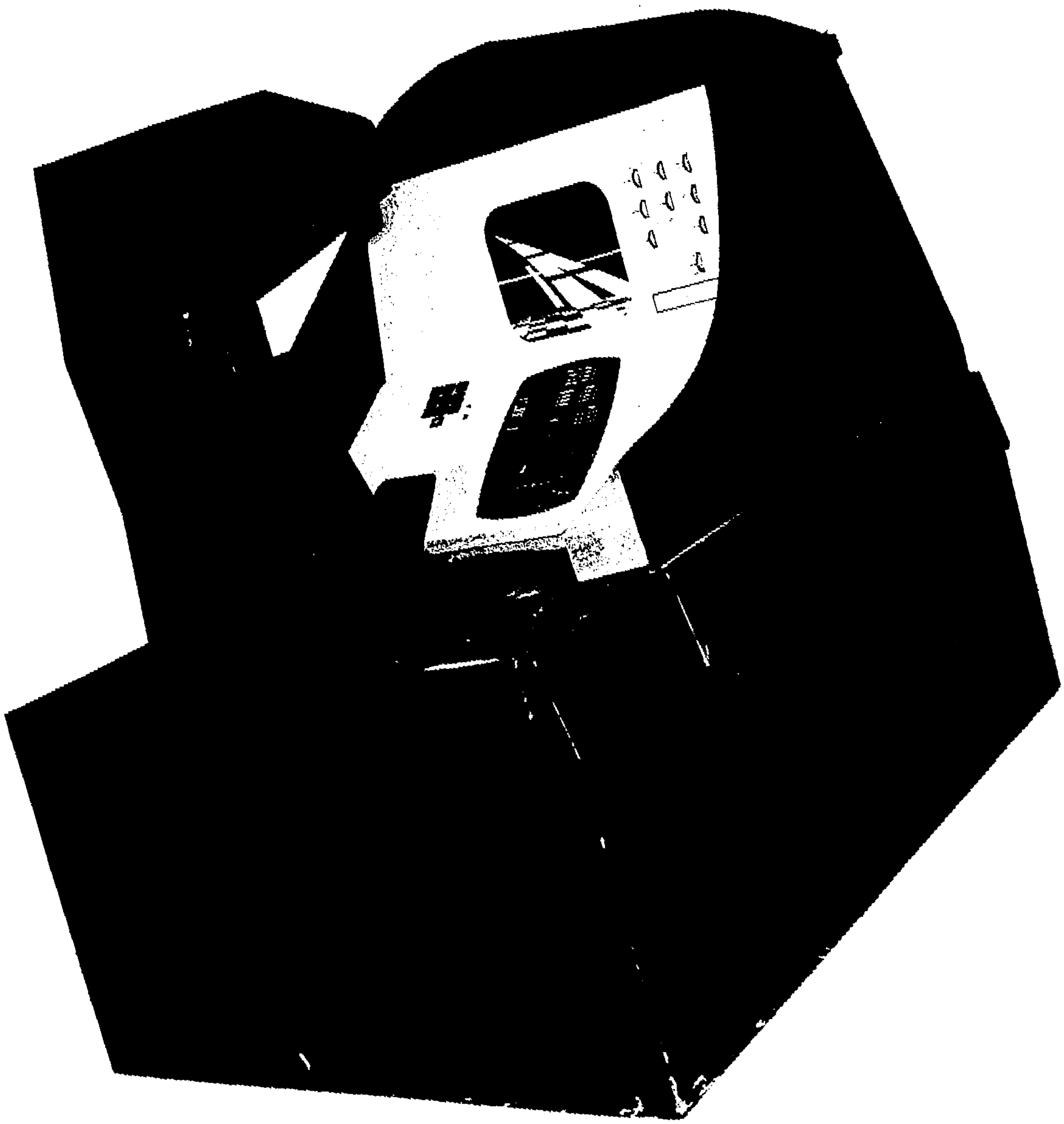


FIGURE 19 CREW STATION MOCKUP

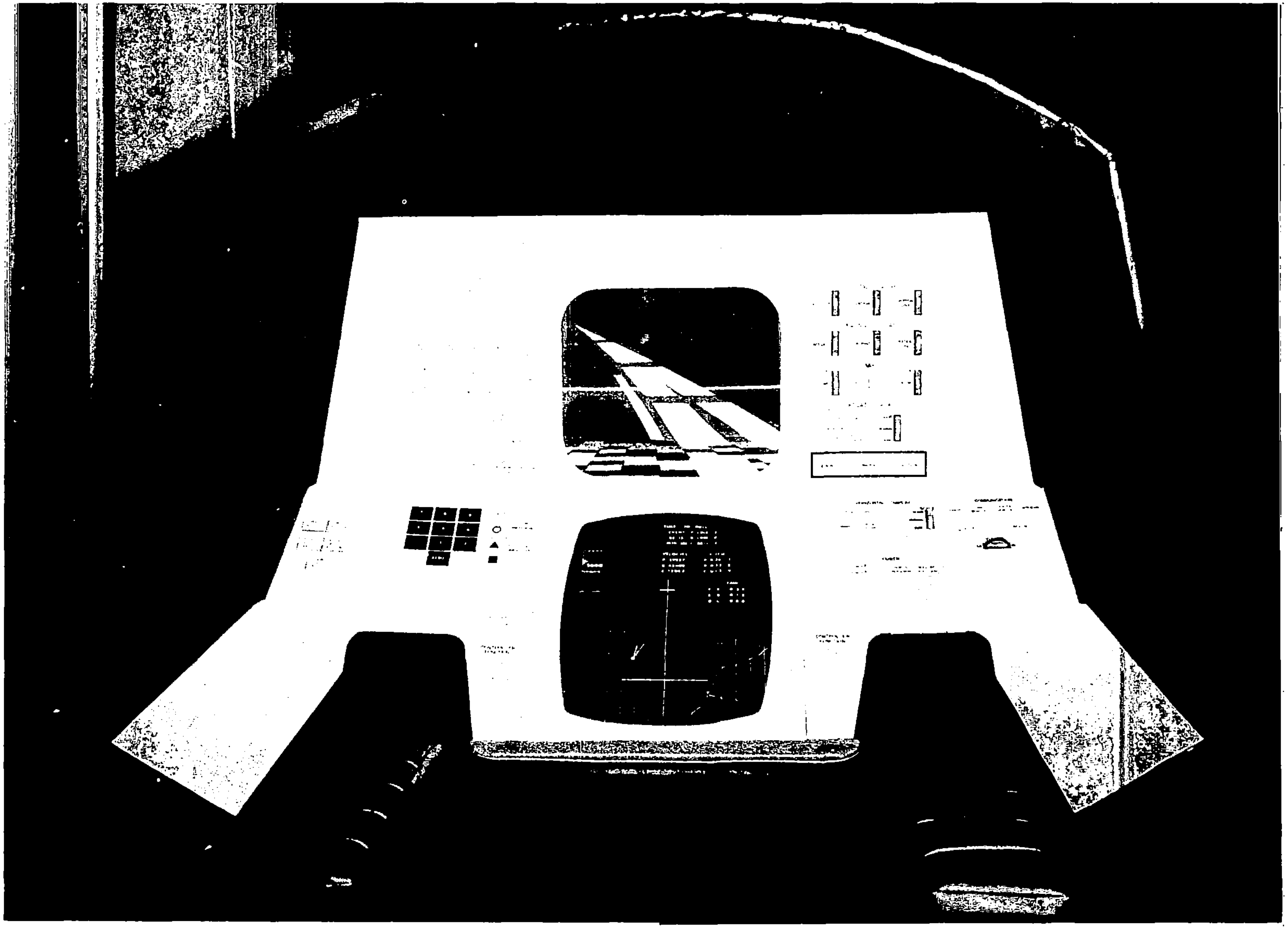


FIGURE 20 CREW STATION MOCKUP DISPLAY PANEL

unless the vehicle was in an extreme pitchdown position (greater than 20 degrees) in which case, yaw should be nulled first, or brought as close to null as possible, followed by pitch and finally roll. At extreme pitch angles, roll and yaw interacted, which led to large and divergent errors in attitude, unless prompt and correct action was taken by the pilot.

Cues for ignition and shutdown were counted down by the Test Conductor, to assure correct pilot interpretation of these display indications.

At the end of the first day of testing, all pilots appeared to have mastered the rudiments of the flight task, and were transitioned to the experimental sequence.

2.5.5 Experimental Procedure

All experimental flights (flights after the first, familiarization day) were conducted in the same manner.

The pilot was asked whether he was ready to go. At the same time, the MAFS Safety Engineer signified the readiness of the simulator. The pilot was then directed to select START PROGRAM at will.

Selecting START PROGRAM made the simulator responsive to pilot control inputs, since this switch enabled the computer. The pilot established a null orientation to local horizontal and the vehicle's orbital path vector. Then, upon request from the Test Conductor, he made an estimate of his position with respect to the nominal path depicted on the Vertical and on the Horizontal Display. He would report being on, above, or below the nominal path, and/or to the right or to the left of that path. The Test Conductor provided feedback, and additional information on orbital shape and position if the initial condition was Number 4 through Number 15. For this group of conditions, the pilot was told that he was in an elliptical orbit, and either ascending or descending. This information was required by the pilot to interpret his initial pitch command, since the first flight objective during thrust was to cancel this negative or positive vertical velocity in such a way that nominal altitude was attained. This nulling of vertical velocity was accomplished by a modified (as compared to nominal) pitch profile.

Approximately three minutes after flight initiation, the pilot was requested to select COMMAND ATTITUDE Mode and to establish the initial attitude indicated. As the subject selected COMMAND ATTITUDE Mode the Nominal path depiction of the Vertical Display was replaced by a Command Path which the pilot flew to, i.e., errors in attitude were shown by the amount of deviation of the path tip from the center of the screen (null point). The pilot steered the center of the display-screen (nose of the vehicle) to the path tip. Local velocity was shown on this command path, as it was on the nominal path, by tar strip motion.

The Horizontal Display in COMMAND ATTITUDE Mode retained the Nominal path, but added a path heading required line emanating from the vehicle symbol, as well as ignition and shutoff lines on the nominal path trace. If the pilot was in the digital information group, the ATTITUDE Mode readout of TIME TO EVENT and PRESENT VELOCITY were supplemented by Required and Change Needed readouts of velocity, and attitude information (present (P), required (R) and change (C) needed, for pitch, yaw, and roll).

During this period the pilot responded to the vehicle subsystem monitoring task. He was instructed to treat this task as secondary, though important. He was not to drop a primary task, such as ignition, for the secondary task. However, because of ingrained past training some pilots continued to respond to the red warning light as a primary task. To correct this, an amber CAUTION alerting display was substituted for the original red WARNING after the first few days of testing.

A minute and a half before ignition, the subject was asked to arm the thrust control by selecting NUCLEAR PROPULSION and THRUST on the console.

The Test Conductor observed the countdown for ignition on the monitor and the ignition input by the subject (by means of a light indicator on the Test Conductor's Console) and informed the pilot how well he had responded to the ignition cue.

Communication during thrust was kept to a minimum. Any interchange made was initiated by the pilot. Little or no coaching of the subject by the Test Conductor or Simulation Engineer occurred during this phase of the flight. Where communication did occur it was documented in the Flight Log.

After thruster shutoff, the pilot was asked to select STOP PROGRAM (which reset the computer), to disarm the thurster control, and to select ATTITUDE MODE on the displays, thereby preparing the crew station for the next flight.

The Test Conductor reported flight path heading, elevation angle, velocity error, and average absolute errors in all three axes to the subjects after each run. This information was read off the ASI printout record made at the instant of shutoff. (SEN). His performance was critiqued, and he was told to prepare for the next flight.

The Test Conductor then instructed computer personnel in attendance which initial condition and task loading tapes were to be used next.

Each flight required fifteen minutes, with about two minutes between flights.

Upon completion of the formal testing period each subject was given the Pilot's Questionnaire to complete within 24 hours. Results of this questionnaire are given in Section 2.6.3 and Appendix I-B.

2.5.6 Simulation Flight Log

During the experimental and evaluative flights, a flight log was maintained of initial conditions, simulation operation, and comments between the Pilot and the Test Conductor.

In this log, the first column indicated the flight number. This number corresponded to that given to the same flight on the digital printouts, and the number assigned that flight in the raw data tables in the RESULTS portion of this report, Section 2.6.

The second column listed the initial condition for the flight. These Initial Condition numbers are the same as those listed in Table 4.

The third column contained the pilot's interpretation of these initial conditions. If he correctly identified the condition, i.e., placed the vehicle in its correct relation to the nominal path, then the entry in the column is "OK." Where the pilot's interpretation was faulty, his interpretation was given.

Notes made on the simulation, including the experimental conditions set up were shown in the fourth column. Any malfunctions which occurred, change in simulation mechanization, etc., were noted in this column.

Finally, the comments made by the pilot during and after each run were recorded in the last column. Explanatory material and Test Conductor comments were in parentheses.

2.6 RESULTS

2.6.1 Injection Point Data Analysis

Of the printout data identified in Table 5, only certain flight injection point items are relevant for evaluating system performance. These injection point parameters are further defined in Figure 21 which also presents their spatial relationships. Median scores achieved for these parameters are given in Table 6. Each of these measures was derived in the following manner:

(1) Scores for each experimental run were transcribed from the ASI printout records onto (subject) x (run) matrices, one matrix for each measure.

(2) On each matrix, the scores were summed over the flights for each subject, and the mean, standard deviation, and median computed.

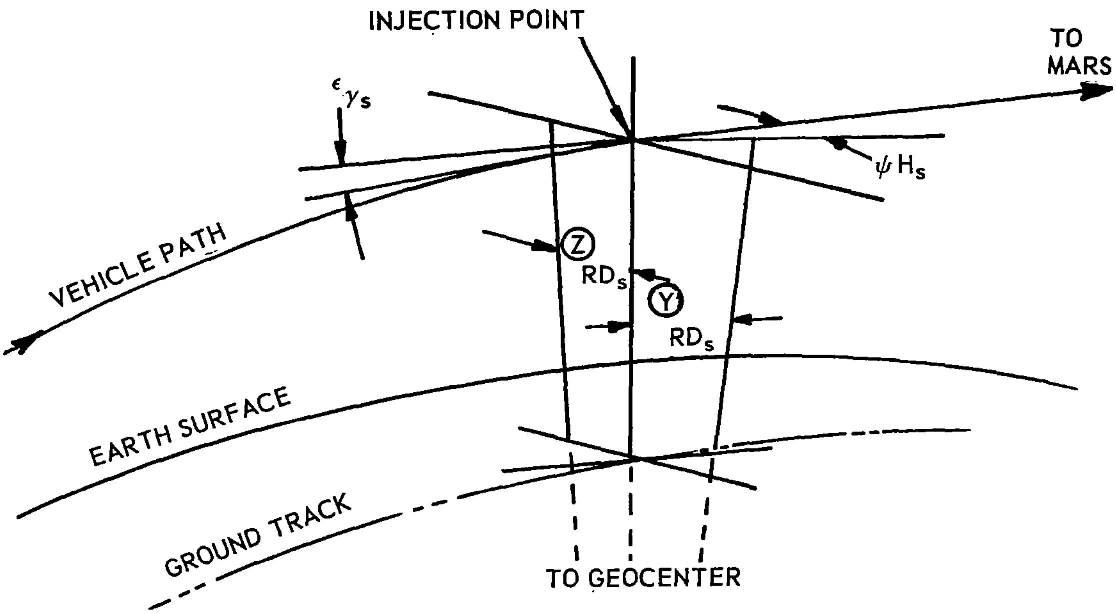
Medians (score above or below which fifty percent of the scores fall in value) are the basic data for analysis rather than means, because many of the sample distributions were markedly skew (i.e., non-normal) as can be seen in Table 7. Skew in these cases were produced by a score or two of the set of scores for a subject being atypical. The subject misinterpreted an initial condition, temporarily reversed responses to the command display, or made some other error. In view of the small number of scores for a given measure, median data, a statistic unaffected by extreme cases in the set of scores, appears to be most descriptive of performance.

The injection point data given in Table 7 are detailed in a series of eleven histograms in which median data per subject are shown for each parameter. In the case of in-plane yaw average error and yaw control energy expended, mean data are substituted for median, since the number of observations was less than four. "In-plane yaw" means an in-plane initial condition for that run.

In the following histograms each bar represents the performance of a particular subject tested under specific group conditions as assigned in Section 2.4.2. These conditions are restated as follows:

CODE	GROUP
I-A	Group I, with Analog information only. (Gain 1.75:1)
I-AD	Group I, with Analog and Digital backup information. (Gain 1.75:1)
II-A	Group II, with Analog information only. (Linear gain change from 8.75:1 to 1.75:1 for errors of 0.1 to 2.0 degrees).
II-AD	Group II, with Analog and Digital backup information. (Linear gain change from 8.75:1 to 1.75:1 for errors of 0.1 to 2.0 degrees.)
II-A(1:1)	Group II, with Analog information only. (True 1:1).
II-AD(1:1)	Group II, with Analog and Digital backup information. (True 1:1)

Specific comments on the data contained in each histogram appear in the explanatory text that accompanies each figure.



AVERAGE ABSOLUTE ERROR	A MEASURE OF CONTROL STABILITY. THE INSTANTANEOUS ABSOLUTE DIFFERENCE BETWEEN COMMAND AND ACTUAL ATTITUDE FOR EACH AXIS OF ROTATION IS SUMMED OVER THE THRUST PERIOD AND DIVIDED BY THE TIME TO ARRIVE AT AN AVERAGE ERROR ESTIMATE.
CONTROL ENERGY EXPENDED (TOTAL)	A MEASURE ANALOGOUS TO FUEL CONSUMPTION. THE INSTANTANEOUS ANGULAR VELOCITY FOR EACH OF THE THREE AXIS OF ROTATION IS SUMMED OVER THE THRUST PERIOD.
TERMINAL VELOCITY ERROR	ENGINE SHUTOFF VEHICLE VELOCITY WITH RESPECT TO THE NOMINAL 42,000 FEET PER SECOND (ABSOLUTE VALUES).
ALTITUDE ERROR	ENGINE SHUTOFF VEHICLE ALTITUDE WITH RESPECT TO NOMINAL 1,800,000 FEET ALTITUDE (ABSOLUTE VALUES).
LONGITUDINAL ERROR (Y) RD_S	ENGINE SHUTOFF POINT POSITIONAL ERROR ALONG PATH MEASURED AS ORBITAL LONGITUDE; CENTRAL ANGLE IN NOMINAL ORBIT PLANE; INJECTION POINT IS CONSIDERED AS ZERO (ABSOLUTE VALUES).
LATITUDINAL ERROR (Z) RD_S	ENGINE SHUTOFF POINT POSITIONAL ERROR OFF PATH MEASURED AS ORBITAL LATITUDE; CENTRAL ANGLE NORMAL TO NOMINAL ORBIT PLANE; INJECTION POINT CONSIDERED AS ZERO (ABSOLUTE VALUES).
ELEVATION ERROR ϵ_{γ_s}	ANGLE BETWEEN THE NOMINAL FLIGHT PATH AND THE ACTUAL VEHICLE PATH IN THE NOMINAL ORBIT PLANE AT ENGINE SHUTOFF (ABSOLUTE VALUES).
FLIGHT PATH HEADING ERROR ψH_s	ANGLE BETWEEN THE NOMINAL FLIGHT PATH AND THE ACTUAL PATH IN THE PLANE NORMAL TO THE NOMINAL ORBIT PLANE AT ENGINE SHUTOFF (ABSOLUTE VALUES).

FIGURE 21 DEFINITION OF FLIGHT INJECTION POINT

FIGURE	MEASURE	DISPLAY GAIN 1.75:1 and 8.75:1 (MIN.)	DISPLAY GAIN 1.75:1 and 8.75:1 (MAX.)	DISPLAY GAIN 1:1 (MIN.)	DISPLAY GAIN 1:1 (MAX.)
	AVERAGE ABSOLUTE ERROR				
22	PITCH (Degrees)	0.691	1.439	0.332	0.450
23	YAW-IN-PLANE	0.658	1.833	0.950	1.250
23	YAW-OUT-OF-PLANE	0.830	2.038	1.218	1.777
24	ROLL	1.085	1.599	0.925	1.281
	CONTROL ENERGY (ANGULAR VELOCITY) EXPENDED				
25	PITCH (Percent)	27.2	43.7	26.4	26.5
26	YAW-IN-PLANE	17.7	35.0	23.1	24.9
26	YAW-OUT-OF-PLANE	23.7	33.2	23.9	25.4
27	ROLL	3.1	8.6	2.4	4.2
	VELOCITY ERROR				
28	ABSOLUTE (Feet per sec.)	1.5	66.4	4.2	4.9
28	ACTUAL	-0.2	66.4	-0.6	2.9
	ALTITUDE ERROR				
29	ABSOLUTE (Feet)	95	259	51	53
29	ACTUAL	5	-259	-32	-51
	LONGITUDINAL ERROR				
30	(Degrees of Central Angle)	0.007	0.037	0.015	0.017
	(Equiv. Nautical Miles)	0.464	2.450	0.993	1.126
	FLIGHT PATH HEADING ERROR				
31	(Degrees)	0.002	0.015	0.003	0.007
	FLIGHT PATH ELEVATION ERROR				
32	(Degrees)	0.001	0.009	0.002	0.004

TABLE 6 SUMMARY OF MEDIAN SCORES - FIRST EVALUATION

			AVERAGE ABSOLUTE ERROR				CONTROL ENERGY EXPENDED				VELOCITY ERROR		ALTITUDE ERROR		LONGITUDINAL ERROR		FLIGHT PATH HEAD. ERROR	ELEVATION ERROR
SUBJECT	CONDITION	PARAMETER	PITCH (DEG.)	YAW IN-PLANE (DEG.)	YAW OUT-PLANE (DEG.)	ROLL (DEG.)	PITCH (DEG/SEC)	YAW IN-PLANE (DEG/SEC)	PITCH OUT-PLANE (DEG/SEC)	ROLL (DEG/SEC)	ABSOLUTE (FPS)	ACTUAL (FPS)	ABSOLUTE (FT.)	ACTUAL (FT.)	(DEG.)	(N.MI.)	(DEG.)	(DEG.)
1.	I-A	MEAN (SD) MEDIAN (in %)	0.784 (0.145) 0.824	1.073 (1.055) 0.658	1.032 (0.436) 0.830	2.041 (1.636) 1.573	1009.3 (153.0) 989.9 43.7%	594.4 (114.4) 549.5 24.2%	687.2 (146.3) 677.3 29.9%	207.1 (421.6) 194.4 8.6%	22.9 (19.2) 11.5	17.4 (24.4) 6.3	112.6 (83.4) 95	-68.2 (122.4) -59	0.017 (0.012) 0.012	1.23 (0.80) 0.80	0.003 (0.003) 0.002	0.003 (0.003) 0.002
2.	I-AD	MEAN (SD) MEDIAN (in %)	1.467 (0.239) 1.439	2.449 (1.609) 1.646	2.708 (1.519) 2.038	2.050 (1.511) 1.599	644.3 (93.9) 615.9 27.2%	519.3 (46.9) 504.9 22.3%	571.9 (51.4) 588.7 26.0%	103.4 (76.9) 79.6 3.5%	67.0 (39.9) 66.4	65.9 (41.6) 66.4	279.8 (177.5) 259	-269.8 (192.2) -259	0.150 (0.290) 0.037	9.93 (19.2) 2.45	0.013 (0.010) 0.015	0.015 (0.021) 0.009
3.	I-AD	MEAN (SD) MEDIAN (in %)	1.105 (0.510) 0.979	1.711 (0.755) 1.833	1.786 (1.132) 1.442	2.306 (1.710) 1.577	755.5 (96.4) 759.7 33.5%	795.3 (158.3) 733.2 32.3%	657.1 (75.7) 628.6 27.7%	142.5 (90.5) 110.2 4.9%	31.9 (28.7) 19.7	31.9 (28.7) 19.7	122.1 (82.2) 136	-108.3 99.6 -136	0.040 (0.045) 0.007	2.65 (2.98) 0.46	0.057 (0.032) 0.004	0.004 (0.010) 0.001
4.	II-A	MEAN (SD) MEDIAN (in %)	1.098 (0.600) 0.888	0.696 (NA) (NA)*	1.852 (1.426) 1.387	1.626 (0.578) 1.574	651.8 (82.9) 633.9 28.0%	401.4 (NA) (NA) 17.7%*	540.4 (62.7) 538.1 23.7%	115.3 (43.7) 132.1 5.8%	7.8 (7.8) 4.9	3.6 (10.4) -0.2	156.9 (87.5) 141	-78.9 (161.4) -125	0.036 (0.045) 0.021	2.38 (2.98) 1.39	0.005 (0.002) 0.005	0.004 (0.014) 0.003
5.	II-A	MEAN (SD) MEDIAN (in %)	1.092 (0.187) 0.981	0.730 (NA) (NA)*	0.984 (0.387) 0.899	1.219 (0.490) 1.085	726.1 (133.6) 743.8 32.8%	517.3 (NA) (NA) 22.8%*	574.1 (99.1) 546.5 24.1%	74.7 (36.5) 69.4 3.1%	7.0 (10.8) 1.5	5.9 (11.2) 0.7	223.8 (195.3) 182	9.1 (282.8) -17	0.011 (0.032) 0.008	0.73 (2.12) 0.53	0.002 (0.002) 0.003	0.003 (0.003) 0.002
6.	II-AD	MEAN (SD) MEDIAN (in %)	0.703 (0.187 0.691	1.249 (NA) (NA)*	1.473 (0.653 1.270	1.445 (0.554) 1.259	690.3 (61.7) 682.2 30.1%	793.1 (NA) (NA) 35.0%*	746.8 (69.0) 752.2 33.2%	129.9 (41.8) 114.5 5.1%	8.4 (7.6) 5.1	7.4 (8.6) 4.9	110.4 (65.5) 109	-32.6 (124.1) 5	0.015 (0.010) 0.017	0.99 (0.66) 1.13	0.002 (0.001) 0.002	0.002 (0.003) 0.003
5.	II-A (1:1)	MEAN (SD) MEDIAN (in %)	0.407 0.179 0.332	1.201 (NA) (NA)*	2.521 (1.749) 1.777	1.718 (0.794) 1.281	589.9 (78.1) 597.5 26.4%	563.5 (NA) (NA) 24.9%*	635.8 (127.6) 542.7 23.9%	91.7 (69.8) 54.8 2.4%	4.9 (3.3) 4.7	1.5 (3.6) -0.6	61.8 (47.8) 53	-28.0 (72.9) -32	0.169 (0.310) 0.015	11.2 (20.5) 0.99	0.005 (0.004) 0.003	0.003 (0.002) 0.004
6.	II-AD (1:1)	MEAN (SD) MEDIAN (in %)	0.467 0.127 0.450	0.950 (NA) (NA)*	1.347 (0.318) 1.218	1.003 0.230 0.925	571.7 (78.3) 599.9 26.5%	524.8 (NA) (NA) 23.1%*	584.3 (36.3) 575.2 25.4%	87.0 (23.6) 94.1 4.2%	6.5 (4.2) 4.2	3.5 (6.9) 2.9	98.2 (99.5) 51	-87.8 (108.9 -51	0.023 (0.032) 0.017	1.52 (2.12) 1.13	0.006 (0.003) 0.007	0.002 (0.002) 0.002

(NA) - Not Available

* - Mean Value Used in Lieu of Median

TABLE 7 INJECTION CONDITIONS - ACROSS TRIALS - FIRST EVALUATION

Figure 22 - Median Pitch Average Absolute Error

This figure shows all subjects with respect to the amount of average error between the commanded pitch attitude and achieved pitch attitude during the thrust portion of the flights. For example, Subject No. 1 maintained a median average error in pitch of 0.824 degrees during all his experimental runs. Note that most of the subjects controlled with an average error of less than one degree. There were no noticeable difference in performance attributable to experimental conditions. As will be seen in the questionnaire answers, subjects used the vertical analog display almost exclusively. Performance differences here were most likely the result of individual skill levels and motivation. Subjects 5 and 6 working under the 1:1 gain condition had the best performance scores for many parameters. This is attributable to learning and to improved operation of the analog command display, since several electro-mechanical servos were replaced by an all-electronic circuit for these 1:1 runs (see Appendix I-A). It might be tentatively said that these subjects scores are representative of the best obtainable with this particular version of the Space Analog for these scores were obtained under near-perfect simulator operating conditions.

Figure 23 - Median Yaw Average Absolute Error

Both median average error for those flights in which the vehicle was initially in-plane (and thus no yaw attitude profile was required, other than null heading) and those runs begun out-of-plane are shown on this histogram. Note that in all cases except Pilot 3, error for the out-of-plane flights exceed that for in-plane. This is because no yaw profile was commanded in an in-plane maneuver, and no yaw rate had to be set up. The pilot simply prevented any error in heading from creeping in as he went through his pitch profile. Therefore, this performance difference in in-plane vs. out-of-plane average error in yaw is not surprising. Yaw average error tends to be greater than pitch error overall. No distinct differences among experimental conditions appear in this plot. The higher error for yaw than for pitch suggests that the Vertical Display did not present yaw error as well as pitch error. The principal cue for yaw error was the "bending" of the path. With a slight amount of roll error, it was possible to fly the vanish point of the command path at the center of the screen with a fair amount of yaw error, unless the "bending" of the path was noted and corrected by a combined roll and yaw attitude control input.

Figure 24 - Median Roll Average Absolute Error

The high error scores shown here are not particularly significant as far as flight management is concerned. Most of the subjects (see Questionnaire results) complained that the roll error cue was difficult to discern after the horizon disappeared during the pitch-down profile. The effect of a more or less constant roll error was slightly coupled pitch and yaw indications. That is, a correction in pitch affected the amount of yaw error depicted, and vice-versa. The subjects were allowing an error in roll (command roll was always zero in this flight) to remain during much of the thrust period. This interpretation of the data is reinforced by Figure 27, Median Roll Energy Expended. None of the subjects used more than 9 per cent of their available roll capability.

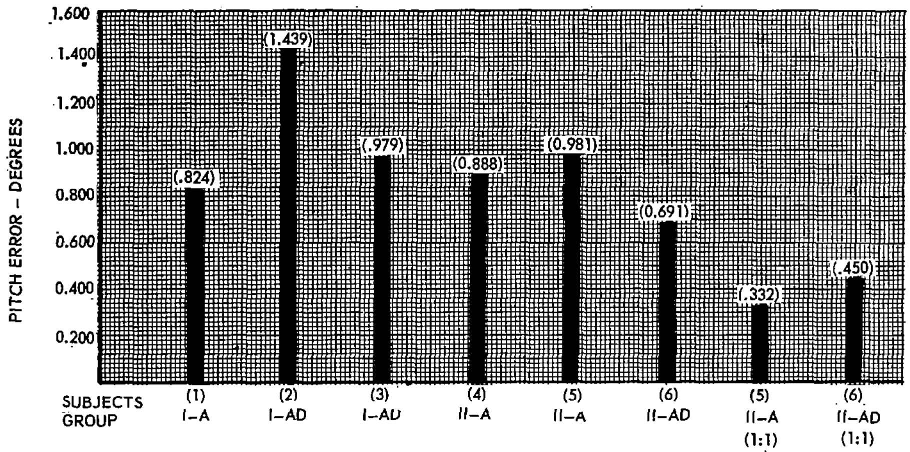


FIGURE 22. MEDIAN PITCH AVERAGE ABSOLUTE ERROR – FIRST EVALUATION

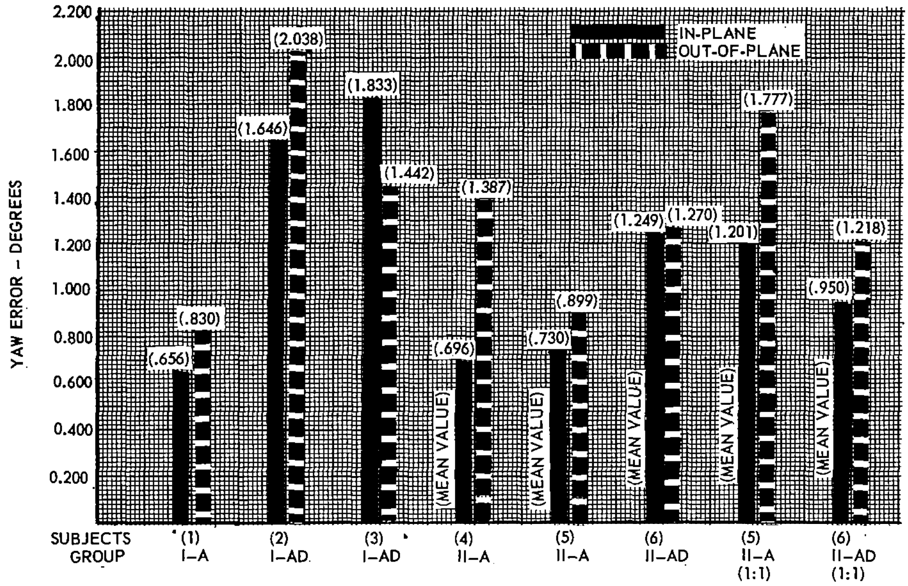


FIGURE 23 MEDIAN YAW AVERAGE ABSOLUTE ERROR – FIRST EVALUATION

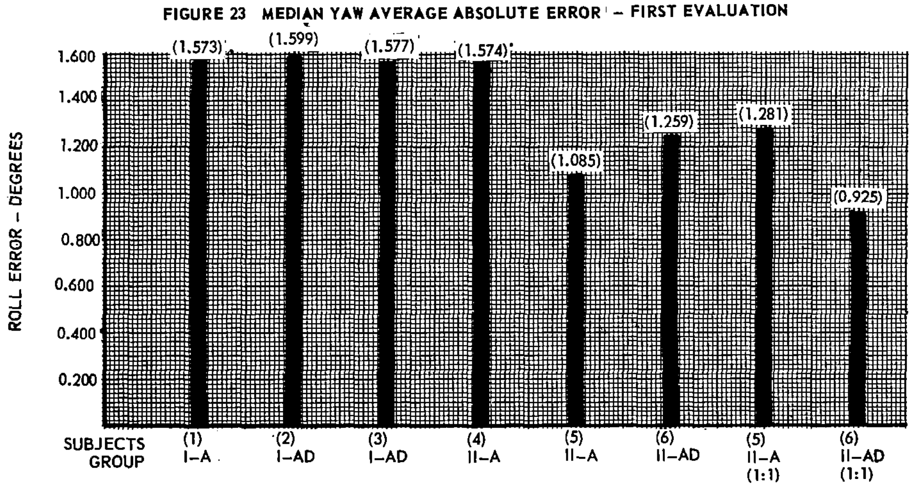


FIGURE 24 MEDIAN ROLL AVERAGE ABSOLUTE ERROR – FIRST EVALUATION

Percentage figures for the next three histograms (Figures 25, 26, and 27 were calculated in the following manner:

$$\text{Pitch \%} = \frac{100 \Delta q_{s_B}}{5 \Delta t_B}$$

$$\text{Yaw \%} = \frac{100 \Delta r_{s_B}}{5 \Delta t_B}$$

$$\text{Roll \%} = \frac{100 \Delta p_{s_B}}{5 \Delta t_B}$$

where: Δt_B = Burn time.

Δq_{s_B} = Pitch angular velocity expended.

Δr_{s_B} = Yaw angular velocity expended.

Δp_{s_B} = Roll angular velocity expended.

for the purposes of this computation, Δt_{B_M} was arrived at by taking the mean burn time for all initial conditions as measured under automatic attitude control.

$$\Delta t_{B_M} = 453.46 \text{ seconds}$$

$$SD_{\Delta t_B} = 5.11 \text{ seconds}$$

Maximum operational capability ($5 \Delta t_B$) is, of course, the same for all three axes in this simulated vehicle. (The amount of velocity expended if the reaction control system were on all during the thrust period.)

Figure 25 - Median Pitch Energy Expended

Note that there were little if any differences among median energy expenditures for the subjects, regardless of condition. Pilot 1, by his own admission, was somewhat heavy-handed on the attitude controller, using a number of "bang-bang" control inputs where a single input would have sufficed.

Figure 26 - Percent Median Yaw Energy Expended

Rather surprisingly, the differences between the in-plane runs and the runs which started out-of-plane seen in Figure 23 for average absolute error are not evident here. It took as much yaw energy to stay in-plane as it did to go through a yaw profile to get into the nominal plane, yet the pilots did not control to as close an accuracy when out-of-plane. Apparently, they had more chance for error in the out-of-plane case.

Figure 27 - Percent Roll Energy Expended

Note the very low energy expenditure for all subjects, and compare this with the high average roll error shown in Figure 24. Subjects were permitting a high roll error to remain without attempting to correct.

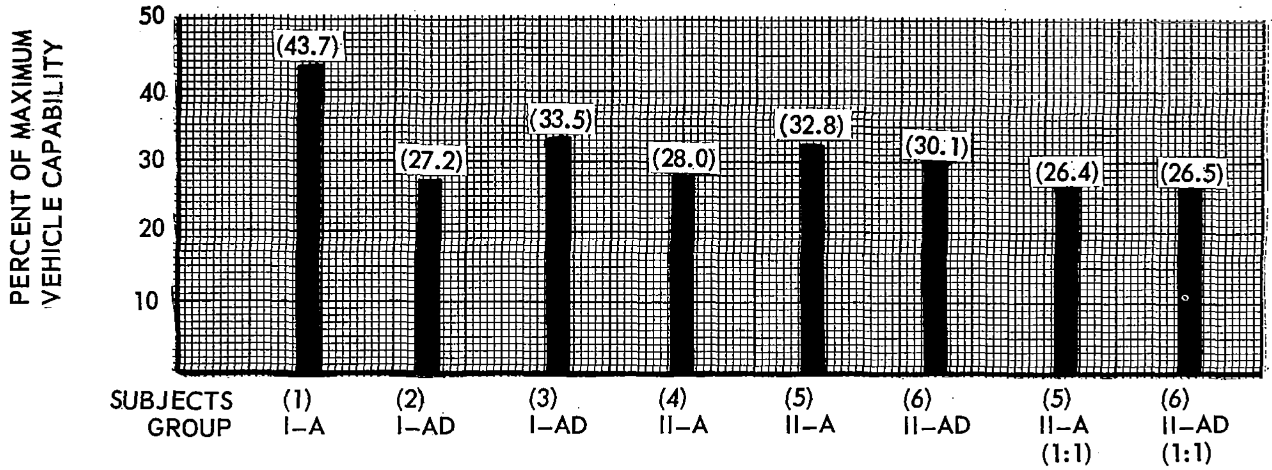


FIGURE 25 MEDIAN PITCH ENERGY EXPENDED – FIRST EVALUATION

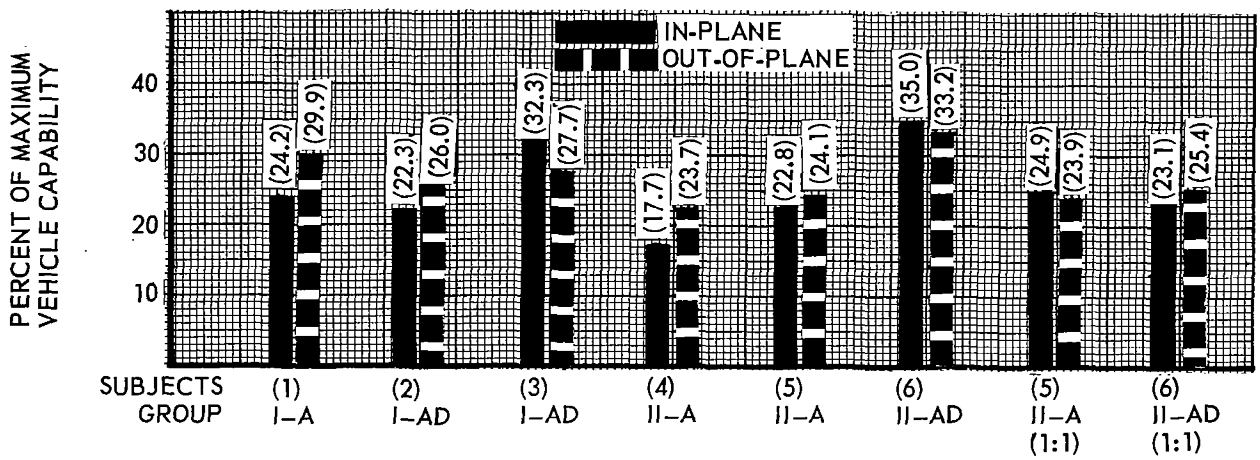


FIGURE 26 MEDIAN YAW ENERGY EXPENDED – FIRST EVALUATION

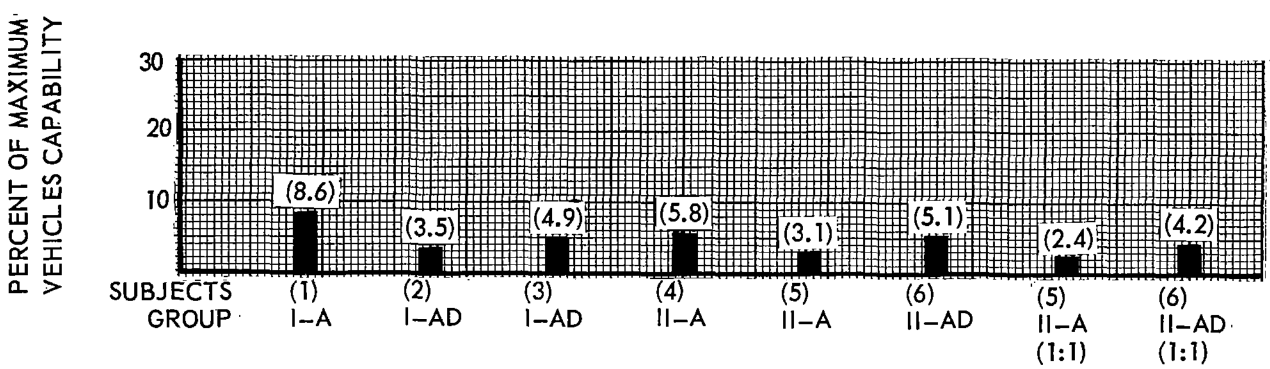


FIGURE 27 MEDIAN ROLL ENERGY EXPENDED – FIRST EVALUATION

Figure 28 - Median Velocity Error at Injection

Both actual (algebraic sum of positive and negative values) and absolute (negative values converted to positive and totalled) medians are given on this plot. It should be noted that very little change in median values occurs when absolute values are substituted for actual values. Subjects showed a tendency to terminate at a velocity in excess of nominal 42,000 fps. Subject No. 4 and Subject No. 5 operating in the 1:1 condition were contrary to this trend with slight negative (slow) median scores.

This overshoot tendency can be explained by assuming either a late response to thruster shutoff cue or by a slightly positive pitch error at shutoff, or by a combination of both. Pilot No. 2's velocity error is twice or more as large as any of the other subjects. This individual missed the shutoff cue several times because he was watching the horizontal display digital readout timer countdown. He failed to transition to the vertical analog display of the cue quickly enough to respond in time to the disappearance of the command velocity markers. A lead term in this cue was incorporated, 0.5 seconds, to compensate for subject latency (see discussion in Appendix I-A, Section 2.5.2.2). However, response time to the termination cue (Δt_{B_O}) for the various subjects varied between 0.57 and 3 seconds, with a mean of about 1 second and therefore 0.5 seconds late, considering the lead term inserted. Lag in response is probably responsible for the positive error in velocity. The need for a more positive thrust termination cue is indicated by this finding. Such a conclusion is supported by the results of the questionnaire, discussed in Section 2.6.3.

Figure 29 - Median Altitude Error at Injection

This histogram shows how well the subjects maintained the nominal altitude of 300 nautical miles at thrust termination. Again Pilot 2 has a high error, but Subject 5 approaches him. The actual scores reflect a tendency (except for Pilot 6) to finish a thrust period below the nominal altitude. Thus, if these findings are combined with those shown in the preceding plot, subjects tended to terminate thrust low and fast with respect to the nominal flight path. This suggests that the pitch profile error may have been positive, or have a positive tendency for most pilots, that is, they pitched down more than the command indicated, but they terminated late, with respect to nominal. This finding is supported by the differential longitude data (Δⓨ$_{RP_B}$) which showed that subjects tended to have negative differential longitude requirement to reach 42,000 fps i.e., they exceeded the velocity requirement at the thrust termination point.

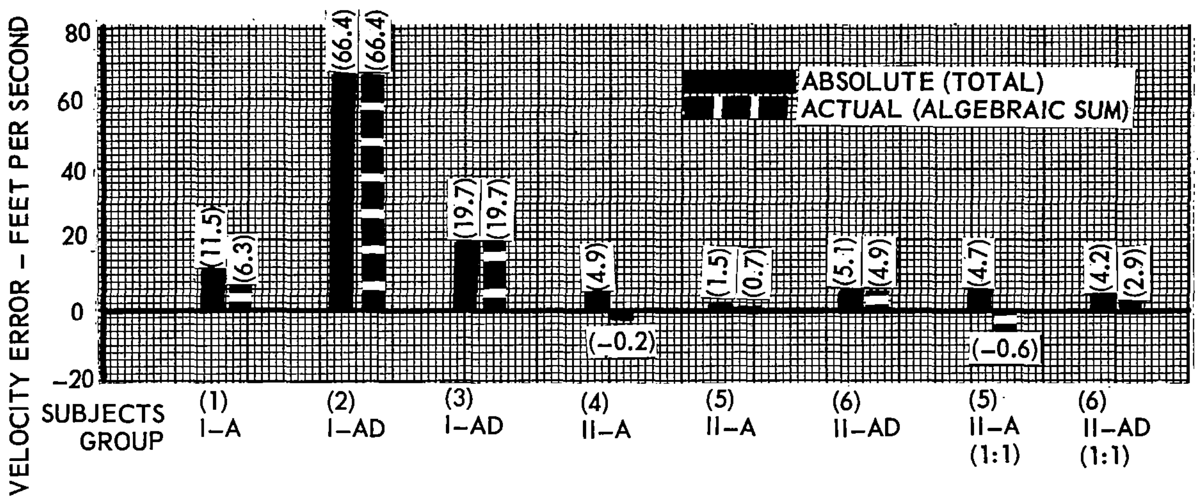


FIGURE 28 MEDIAN VELOCITY ERROR AT INJECTION – FIRST EVALUATION

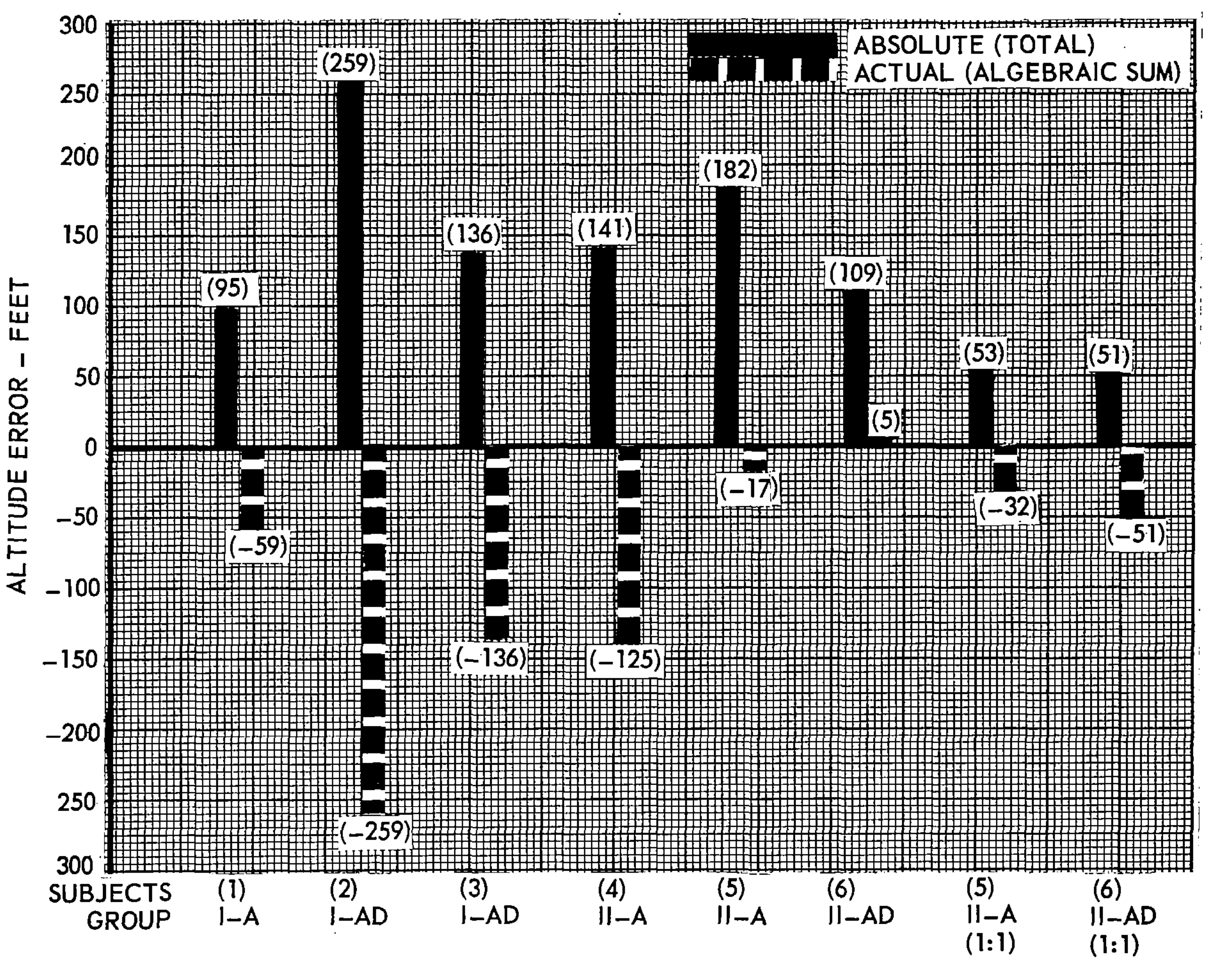


FIGURE 29 MEDIAN ALTITUDE ERROR AT INJECTION – FIRST EVALUATION

Figure 30 - Median Longitudinal Error at Injection

These data were derived in the following manner:

$$\Delta \textcircled{Y}_{RP_B} = \textcircled{Y}_{RP_S} - \textcircled{Y}_{RP_F} - \frac{57.3\ V_S}{r_s}\ \Delta t_{B_O}$$

where: $\textcircled{Y}_{RP_S}$ = Longitude at thrust termination.

$\textcircled{Y}_{RP_F}$ = Longitude at thrust initiation.

V_S = Vehicle velocity at termination.

r_s = Altitude at termination + 20,926,080 feet (termination radius).

57.3 = Conversion factor from radians $\left(\frac{V_s}{r_s}\right)$ to degrees.

$$\Delta t_{B_O} = \frac{\epsilon\ v_s}{\left(\frac{T}{M}\right)_s \cos \theta_s}$$

The measure gives the amount of central angle in longitude that must be traversed at the thrust termination velocity to reach 42,000 fps, the nominal injection velocity. There were no significant differences among experimental conditions. Median latitude error at thrust termination, $\textcircled{Z}_{RD_S}$, was essentially zero for all subjects. Pilots were within $\pm$.001 deg(central angle) of being in plane when thrust termination occurred.

On this histogram 0.01 degree equals 0.6622 nautical miles.

Figure 31 - **Median Flight Path Heading Angle Error at Injection**

These data should be considered with Median Flight Path Elevation Error which is shown in Figure 32. These two parameters reflect the "aiming" accuracy of the pilots at thrust termination. Median error (deviation from nominal heading) was never more than 0.015 degrees, or less than a minute of arc, well within requirements for orbital injection.

Figure 32 - **Median Flight Path Elevation Angle Error**

Median error (deviation from nominal path elevation) was never more than 0.009, or half a minute of arc.

The above two quantities reflect control accuracy, especially during the terminal thrust stage.

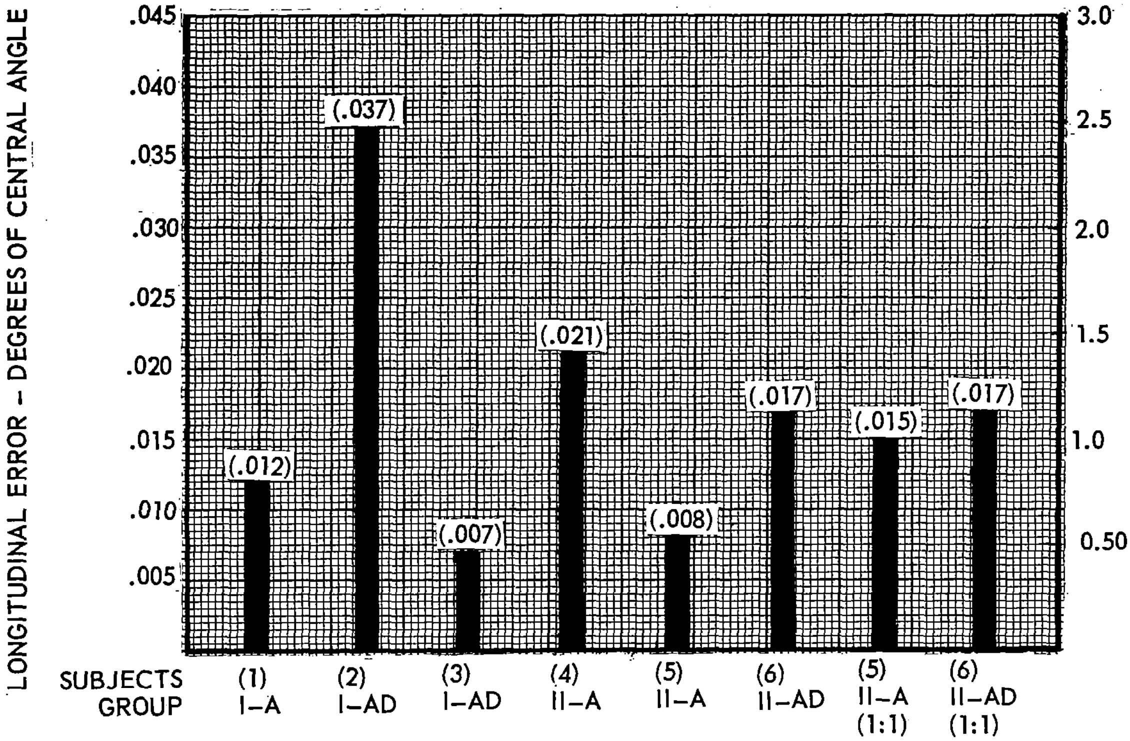


FIGURE 30 MEDIAN LONGITUDINAL ERROR AT INJECTION - FIRST EVALUATION

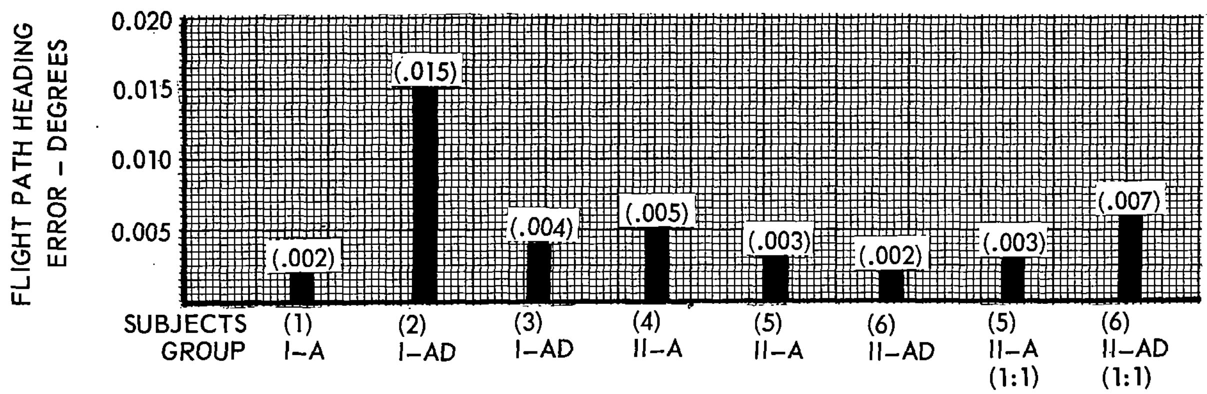


FIGURE 31 MEDIAN FLIGHT PATH HEADING ERROR AT INJECTION - FIRST EVALUATION

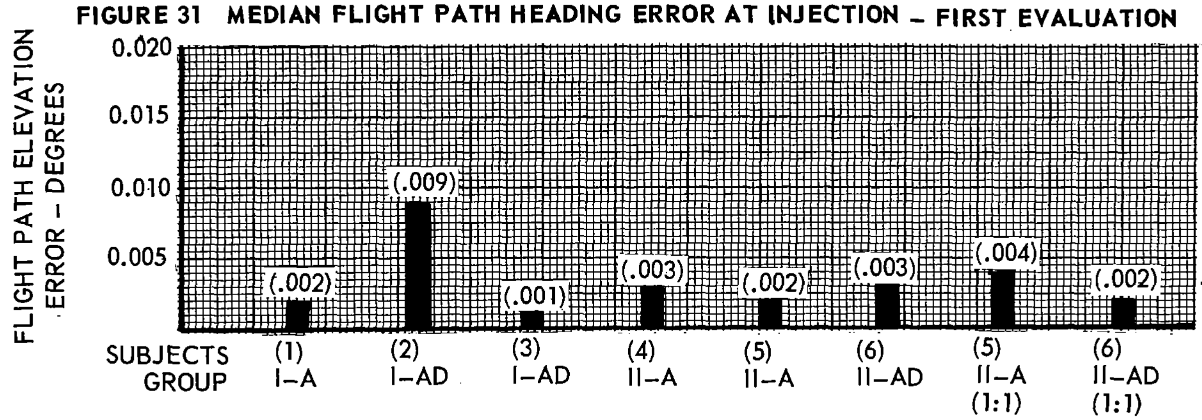


FIGURE 32 MEDIAN FLIGHT PATH ELEVATION ERROR AT INJECTION - FIRST EVALUATION

2.6.2 Mann-Whitney "U" Test

The large amount of variance in the data, the skewed distributions, and the low number of trials run in the experimental period make any use of parametric tests of significance questionable. Consequently, the median data were converted into ranks across experimental conditions for each performance measure, so that a non-parametric test of significance, the Mann-Whitney "U" test for 2 Independent Samples, could be applied to the data. Two such tests were run on each performance measure; one test between Display conditions (Analog vs. Analog plus Digital information) and the other test between display gain conditions (Gain 1.75:1 vs. Variable Gain). The 1:1 gain condition was not tested, because there were insufficient data for any meaningful comparison.

In the Mann-Whitney Test (Reference 9) scores which achieve at least ordinal level of measurement are converted into ranks, retaining group identity in the conversion. One of the two groups is arbitrarily selected as the group of interest. Then a count is made of the number of times that a score, in the rank order, which comes from the other group, precedes a score from the group of interest. This number, the statistic "U", will be around a half or more of the total number of scores in the ranking because the scores from the two groups will be intermixed in the rank order. But "bunching" of scores, from either the group of interest or the other group, will produce a low "U." The distribution of the "U" statistic is known and tabled for various size groups. These tables give critical values for the one-tailed hypothesis, i.e., significant differences either positive or negative, but not both, between groups which result in rejecting the null hypothesis of no group differences. In the present study both positive and negative differences are relevant. Hence, the critical values in the tables are doubled to provide a test of the two-tailed hypothesis.

With this test, the researcher is testing the probability that a possible score from one group is either larger or smaller than a score from the other group. The Mann-Whitney is one of the more powerful non-parametric tests, and is widely used as a less restrictive alternative to the parametric "t" test.

Results of the Mann-Whitney analysis of median data is presented in Table 8.

In the tests between the Analog Only and Analog plus Digital information conditions, Table 8 shows that significant differences were in favor of the analog-only group. That is,subjects who did not have digital information tended to control better, as measured by yaw control and velocity

MEASURE	A - AD COMPARISON		GAIN COMPARISON	
	LEVEL	TREND	LEVEL	TREND
ABSOLUTE ERROR				
PITCH	N.S.	None	N.S.	None
YAW-IN-PLANE	0.10	Analog Only	N.S.	None
YAW-OUT-OF-PLANE	0.20	Analog Only	N.S.	None
ROLL	N.S.	None	0.20	Variable Gain
CONTROL ENERGY EXPENDED				
PITCH	N.S.	None	N.S.	None
YAW-IN-PLANE	0.20	Analog Only	N.S.	None
YAW-OUT-OF-PLANE	N.S.	None	N.S.	None
ROLL	N.S.	None	N.S.	None
VELOCITY ERROR				
ABSOLUTE	0.20	Analog Only	0.10	Variable Gain
ACTUAL	0.20	Analog Only	0.10	Variable Gain
ALTITUDE ERROR				
ABSOLUTE	N.S.	None	N.S.	None
ACTUAL	N.S.	None	0.20	Gain 1.75:1
LONGITUDINAL ERROR	N.S.	None	N.S.	None
FLIGHT PATH HEADING ERROR	N.S.	None	N.S.	None
ELEVATION ERROR	N.S.	None	N.S.	None

A-AD - Analog Only to Analog Plus Digital
Level - Level of Significance (2-Tailed Probability)
Trend - Which Group Did Better
N.S. - No Significant Difference

TABLE 8
MANN-WHITNEY "U" TEST RESULTS
FIRST EVALUATION

maintenance, than those with digital inputs. The questionnaire data suggests that the digital information tended to distract the subjects, as presented in this simulation. It is possible that other ways of displaying numerical data might not lead to these results. The level of significance, except for yaw average absolute error--in plane, was very low, 0.20.

The tests between gain conditions tend to favor the Variable Gain condition, a linear change from 1.75:1 to 8.75:1. Velocity error was affected by this variable; and, since this in turn was affected by pitch control, it may be that the greater sensitivity of the display to attitude error in the Variable Gain condition can account for this significant difference. Altitude error was better for the Gain 1.75:1 condition than Variable Gain, but the level of significance was very low.

Some of these trends as reflected by tests of significance are interesting, but individual differences in performance fairly well swamped what differences may exist between experimental conditions. The above results should therefore be interpreted very cautiously.

2.6.3 Questionnaire Analysis

The Pilot Questionnaire was administered to all subjects following their participation in the study. The questionnaire format, the rating scales used, group results and individual responses are given in Appendix I-B.

As a summary of the questionnaire the following statements can be made:

(1) Pilots did little scanning between the Vertical and Horizontal displays. Instead, they fixated on the Vertical Display, with but occasional glances at the Horizontal display.

(2) Pilot opinion was that the vertical analog display satisfactorily fulfilled the mission requirements of managing orbital change.

(3) The pilots considered the vertical display as being easy to interpret in both situation and command modes, much superior to other forms of situation presentation and somwhat superior to other forms of attitude command presentation.

(4) Roll presentation was more difficult to interpret than pitch and yaw, mainly because the horizon line was not visible in pitch attitudes greater than ±11 degrees.

(5) The velocity marker motion used for thrust initiation and termination was considered to be less effective than an indicator light at the side or top of the display would have been.

(6) The Horizontal Display presentation was somewhat blurred and considered too gross to be of much use to the pilot during this maneuver. Digital information was used extensively by only one pilot, while the others only used attitude change readouts to some extent.

(7) The system monitoring task was overemphasized as to importance by some pilots, but none were task loaded to any significant extent during the thrusting sequence. Time was apportioned appropriately. The pilots were evenly divided with respect to opinion of systems information presentation; half liked a random sampling scheme to cut down systems status display clutter in the cockpit, while half preferred to have the information always available.

2.6.4 Discussion

These data and the questionnaire material suggest that the independent variables studies in this program had little if any effect on the pilot's performance. The constant condition, the vertical display, was adequate to manage the cisplanetary injection profile. Digital information only served to distract several subjects, although this might have been due to its being presented on the horizontal display, and its being presented with inferior clarity. But, certainly, no case can be made for the necessity of digital information on the basis of this simulation. Analog information was sufficient to control the vehicle, and to follow through an attitude command profile.

The results for display gain are inconclusive, mainly because insufficient data were collected for a true 1:1 gain conditions. The display was always more sensitive to error and to corrective inputs by a factor of 1.75. The small amount of information obtained under 1:1 does suggest that larger than 1:1 gain is not required for adequate injection management. The effect, on the pilot, of the high-gain type display used in this evaluation is that of an error display which becomes somewhat more jittery as zero error is approached. However, this increased sensitivity does not necessarily lead to more accurate attitude control. The pilot appeared to be reacting to the increased sensitivity as if it were noise.

The horizontal planning display had little or no role in this study other than providing a realistic crew station environment. It is basically a long-range planning display, and a panel on which subsystem information was presented. No long-range planning was required for this particular orbital injection. The vertical display informed the pilot as to what to do and when to do it. The path heading presentation, and thrust initiation/termination lines were useful for general planning of the maneuver and not intended to compete with the greater accuracy of the vertical display. In the Second Evaluation, a vastly simplified horizontal display will be used which will only show vehicle position with respect to nominal, for "how goes it" information.

The task loading sequence succeeded in its principal purpose--providing the pilot with a realistic amount of work in the cockpit, though it would have been better had more variety been built into the sequence, perhaps with several levels of information capability of presentation.

The vertical display functioned very well as a nulling display of the "follow me" variety. It led the pilot through the whole thrust profile. If he followed its instructions exactly, "steering" in the direction commanded by the path, he made a successful injection. The data are conclusive on this point. The Space Analog display as used in this study is a feasible command display. The path depiction is analogous to the highway which provides the heading command for the motorist. But, like the motorist who has no road map, the pilot must trust the display generation that he will actually arrive at his objective by following the path. He has no "how am I doing" information, except for the horizontal plane information shown on the horizontal display.

A significant problem is, the non-intuitive relationship between attitude and velocity vector in space flight, especially if orbital dynamics are considered as well. Pointing the nose of the vehicle at the required path will not necessarily put it on that path. In the present study, the pilots could have dispensed with "what am I doing" information provided by the ground reference plane, since they were locked into the command path, and had no nominal path depiction to relate their present position to. Had the pilots been presented two paths, the command attitude and nominal, on the vertical display, understanding of the flight situation would have been better, and the "how am I doing" fundamental question answered, as the command path led the pilots ever closer to the nominal--desired trajectory. However, it was not possible to show both paths in true relationship to the real world at the same time due to the limited view angle of the vertical display and the extreme attitudes required by the vehicle when thrusting along its longitudinal axis.

This study has established the feasibility of analog-type command attitude displays for conveying all necessary information for flight control of a fixed booster, constant-thrust space vehicle. All pilots and many visitors considered the display of attitude and command attitude information to be superior to, and more easily interpretable than, any space flight hardware now in use.

These study results have shown that, analog information is adequate to manage an orbital change, the most fundamental of all space flight maneuvers. Therefore, methods of presentation and types of analog information should now be investigated to provide the answers to all four of the fundamental vehicle control questions:

(a) What am I doing?

(b) What should I be doing?

(c) How am I doing?

(d) How should I be doing?

Such combination must be integrated within a single display, so that in one view the pilot can obtain all the information required to adequately perform his role in the space vehicle system.

2.6.5 Conclusions and Recommendations

2.6.5.1 Conclusions

(1) Vertical Display Performance - The Vertical Display, with a flight path presentation of command attitude and thrust initiation and termination cues is an acceptable means of performing an orbital change space maneuver. Test subjects considered it to be the equal of or superior to any other type of command attitude display with which they have had experience. Subject performance supports this opinion. With the analog format used presented on a standard television raster of 512 lines and a view area of 8 x 10 inches with a 1:1 relationship to the real world, the following flight performance was achieved:

	No Display Gain (1:1) Average of Median Scores
Velocity Error	4.6 feet per second
Altitude Error	52 feet
Out of Plane (lateral) Position Error	Essentially zero
In Plane (longitudinal) Position Error	1.07 nautical miles
Flight Path Heading Error	0.005 degrees
Flight Path Elevation Error	0.003 degrees

(2) Vertical Display Gain - Increased gain had little effect upon attitude control accuracy. Step Gain, a sudden five fold increase in sensitivity of the attitude error displayed (at 1 degree and below) was found to be very disruptive to the pilot. Variable Gain, wherein the increase of sensitivity is linear over an error range of 1.9 degrees (from 2.0 to 0.1) was acceptable.

It is possible that higher gains for a given of attitude error (ten or twenty to one) might lead to greater control accuracy, but this must be traded off with "jitter" effects on performance with a slow responding spacecraft. Preliminary investigations of 17.5:1 in the present study proved unsatisfactory in that the system was unstable. Another approach which can be taken in this area is in quickening the display by presenting the first and perhaps the second derivative of the error. This approach has led to improved control performance in other slow response systems such as submarines.

(3) Deficiencies in Command Attitude Presentation - The format evaluated did not provide adequate task performance information ("how am I doing"). The pilot was not able to determine his approach to the nominal path, how far he still had to go, and when he would be on nominal. The pilot had to trust the display to take him to the nominal path he was attempting to attain.

Roll cues from the reference surface were relatively weak once the local horizon was no longer in view. This can be alleviated by increasing the texture gradient of the reference surface, i.e., presenting more of the quasi-random square surface pattern by an apparent increase of vehicle altitude.

(4) Need for Digital Information - Digital information was not necessary to perform the orbital change maneuver. The vertical display was clear and unequivocal in the command mode.

(5) Space Analog Horizontal Display - The horizontal display was not required for the accomplishment of the orbital change maneuver. It was used only as a backup for situation information. The need for this display would have been greater had the simulation included the preceding cisplanetary injection planning phase.

(6) Training Requirements for the Space Analog - Comparatively inexperienced pilots and even non-pilots learned to make an acceptable injection in just a few trials. The vertical display presentation is sufficiently like the cues that are obtained in other more familiar vehicle management situations, and presents command information in a sufficiently straightforward manner, that positive transfer takes place. The integration of information in this display makes a complex and difficult task much easier and natural.

(7) Acceleration Mode Attitude Control - In this mode the attitude controller, when actuated, produced a constant angular acceleration about the axis commanded. To cancel the rotation imparted to the vehicle required an opposite deflectinn of the control for an equal period of time. It was quickly determined that the vehicle was virtually unmanageable when in the Acceleration Mode. Angular rates achieved, rapidly reached the limit of scaling in the ASI-2100 digital computer, and resulted in computer shutdown. It was the opinion of the pilot that the mode "could be learned" but not without considerable practice time.

Rate attitude command was used for all subsequent flights.

(8) Task Loading - The Task Loading was fairly effective, and differences in performance rate between coast and thrust periods were noted, as expected. But a more continuous task is necessary to ascertain the points during the thrust period at which primary task loading occurs.

2.6.5.2 Recommendations

The majority of the following recommendations are directed toward the further development of the analog concept of information display for orbital change space maneuvers: and as such also serve as the base requirements for the second simulator evaluation.

(1) Vertical Display Format - Revise the information format of the vertical display as follows:

(a) Vehicle Coast Period - Presentation to be the same as in the First Evaluation, i.e., view forward (center of the display screen) represents the direction the vehicle is pointed. The background, reference surface, horizon, sky texture and nominal flight path are presented in a true 1:1 real world relationship to the line of sight. This mode remains as the ATTITUDE MODE.

(b) Vehicle Thrust Period - Presentation is changed from that of the First Evaluation wherein the flight path represented command attitude and the view forward the direction the vehicle was pointed. In the revised format the flight path and the background are the same as in the ATTITUDE MODE above. However, the view forward (center of the display screen) now represents the direction of the vehicle flight path (vector). This change now permits the presentation of "how am I doing?" information in that there is a positive presentation of vehicle position with respect to the nominal path at all times during the thrusting maneuver. This mode is now identified as the PATH MODE.

(2) Vertical Display Scaling - Provide scale changes in both lateral and vertical vehicle positional error display to permit the study of flight techniques for acquiring the nominal path when the vehicle is off path by a significant amount. The ability of the pilot to re-acquire a nominal path following either poor pilot technique or system malfunction during the previous flight maneuver would reduce the need for pilot navigational effort and vehicle computer capacity to reprogram the nominal path after each flight path error.

(3) Horizontal Display Format - Delete digital backup data and required vehicle path heading. Retain the nominal path, vehicle position, present vehicle flight path heading, thrust initiation and termination lines, and background reference grid and terrain texture as planning information for the orbital change maneuver. In addition retain the status-trend display for vehicle subsystems as task loading during the simulation.

(4) Simulation Performance Comparisons - Upon completion of the Second Evaluation compare the flight performance with that of the First Evaluation to determine the significance of the added "how am I doing?" information.

3.0 SECOND EVALUATION

The purpose of the Second Evaluation was to establish the operational effectiveness of, and requirements for, an advanced Space Analog Vertical Display incorporating a real world analog display format. This format corrects the task performance information ("how am I doing") deficiencies inherent in the command attitude display of the First Evaluation. Testing consisted of 84 experimental flights in the LTV MAFS during the period 21 June through 13 July 1966.

3.1 OBJECTIVES

The objectives of the Second Evaluation were:

(1) To assess pilot performance when using a Space Analog Vertical Display wherein the view is in the directionthe space vehicle is moving (velocity vector) and is presented in proper relationship to the required (Nominal) path and a background representative of the real world (ground texture, horizon, and sky plane).

(2) Compare pilot performance during the Second Evaluation with that in the First Evaluation.

(3) Establish requirements for displays and controls that have been validated through simulation results and define requirements for further investigations.

3.2 THE SIMULATION PROBLEM

3.2.1 The Space Mission Segment

The mission segment for the Second Evaluation was the same as for the First Evaluation for purposes of obtaining a direct comparison of pilot performance (Section 2.2.1 and Figure 2). Though the flight profiles were the same the differences in individual flight problems were visually more apparent in the Second Evaluation. The command attitude presentation of the First Evaluation appeared to be the same for all flight problems. However, in the Second Evaluation the presentation of space vehicle direction of motion resulted in a realistic view of each flight situation. This is best illustrated by a comparison of Figures 33 and 3.

3.2.2 Simulated Space Vehicle

The same space vehicle configuration was used as in the First Evaluation (Section 2.2.2 and Table 1).

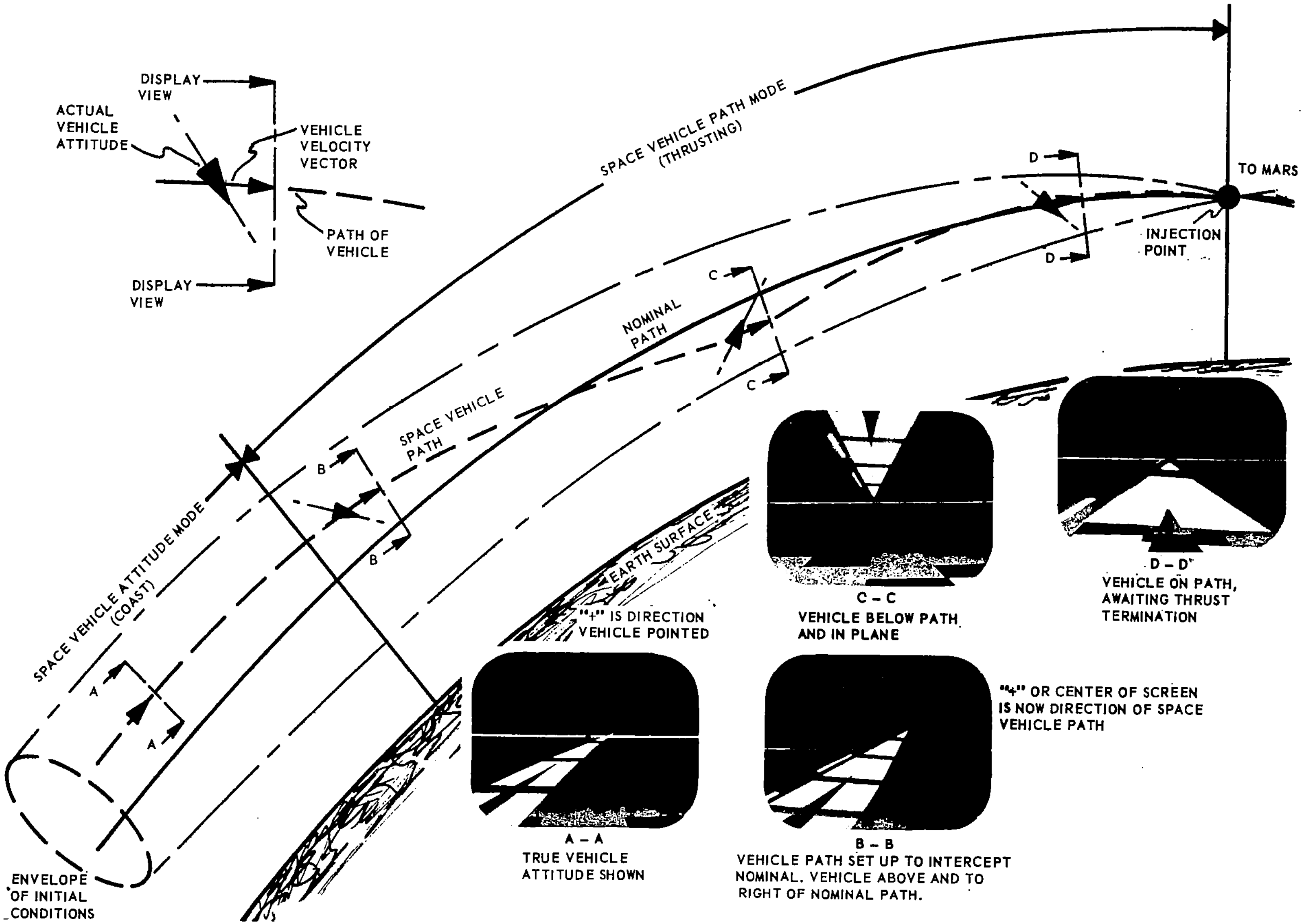


FIGURE 33 TYPICAL FLIGHT PROFILE – SECOND EVALUATION

3.3 SIMULATION SETUP

The hardware setup for the Second Evaluation, consisting of the LTV MAFS crew station gondola, hybrid digital-analog computer, etc., was the same as for the First Evaluation (Section 2.3) with the following exceptions. (Certain descriptions are repeated for clarity.)

3.3.1 Crew Station Displays and Controls

Revisions to the crew station were limited to the information content on the vertical and horizontal displays (a computer program change) and a new control procedure for clearing the task loading CAUTION light.

(1) Vertical Display

Two display modes were used:

(a) Space Vehicle Attitude Mode - Same as the attitude mode in the First Evaluation (Figure 8) wherein the presentation is a true view forward of the vehicle nose. This mode is used primarily during the initial coast period to permit vehicle attitude orientation in preparation for vehicle thrust initiation. Thrust command being a part of the Path Mode.

(b) Space Vehicle Path Mode - This mode was substituted for the Space Vehicle Command Mode of the First Evaluation to provide the pilot with task performance or "how am I doing" information during the thrusting maneuver.

The center of the display screen represents the direction the space vehicle is moving (flight path velocity vector). This view forward is oriented with respect to the Nominal Path and the background consisting of the ground reference plane, horizon line, and sky plane. The Nominal Path is the ideal earth orbital path required to attain the cisplanetary injection point.

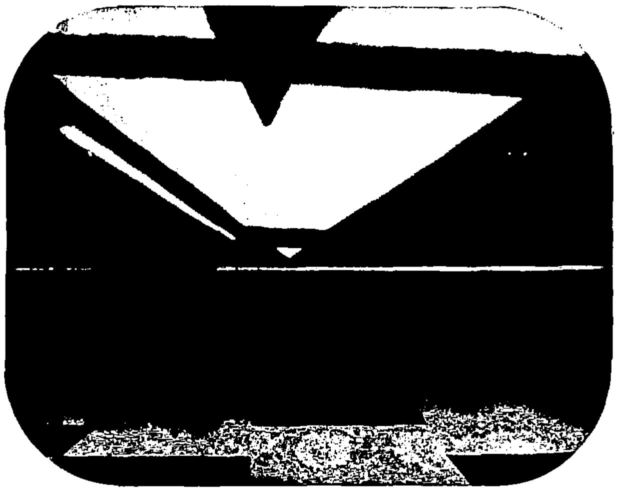
Typical presentations in the Space Vehicle Path Mode are shown in Figure 34.

Initially the Path Mode was unflyable when vehicle path elevation and heading error displays (relationship of the center of the display to the tip of the Nominal Path) were in a 1:1 relationship with the real world. The small angles involved in the injection maneuver, and their rates of change, were not discernible to the pilot. Consequently, in the course of the engineering shakedown flights, and prior to the start of testing, display gain values were incorporated progressively, with trial flights following each gain increase, until a flyable configuration was arrived at. Final gain values used were:

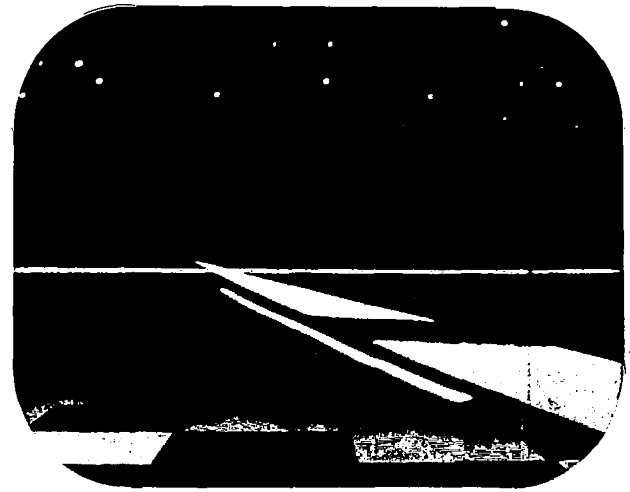
Vehicle Path Elevation Angle Error Gain - 6 : 1

Vehicle Path Heading Angle Error Gain - 32 : 1

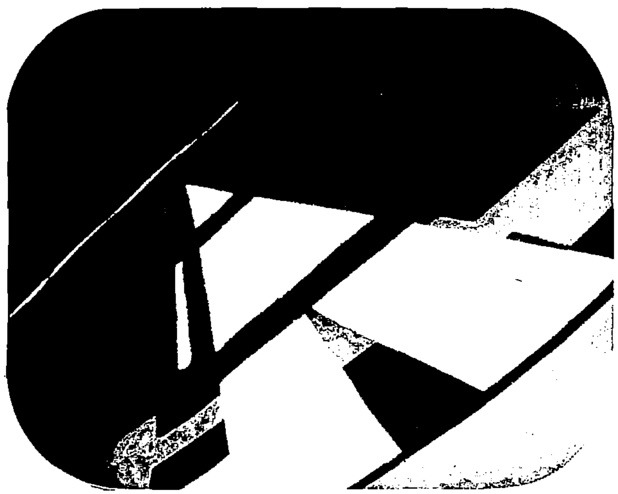
The additions of the above gains had one detrimental effect upon the realism of the vertical presentation. Large errors in vehicle path elevation and heading were magnified by the gain and resulted in excessive displacements of the Nominal Path with respect to the background. To minimize these distortions,



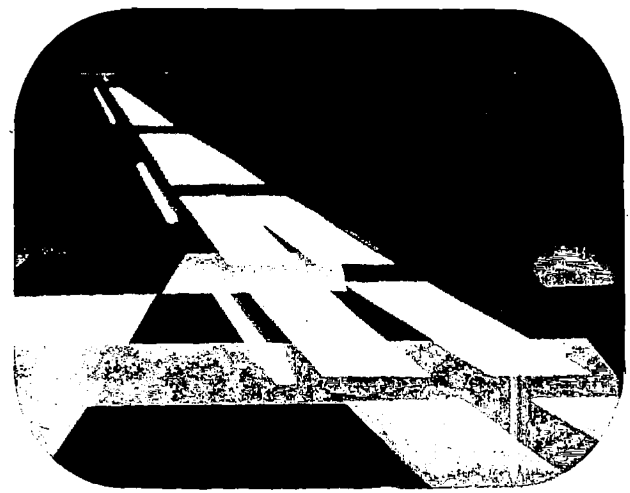
VEHICLE ON NOMINAL PATH BUT SLIGHTLY BELOW REQUIRED ALTITUDE



VEHICLE AT REQUIRED ALTITUDE BUT TO LEFT OF NOMINAL PATH. ON INTERCEPT COURSE.



VEHICLE ABOVE NOMINAL PATH AND ROLLED RIGHT. ABOUT TO PASS THROUGH PATH AND CROSS OVER TO THE RIGHT.



VEHICLE ABOVE AND TO LEFT OF NOMINAL PATH. ON INTERCEPT COURSE.

FIGURE 34 VERTICAL DISPLAY PRESENTATIONS – SPACE VEHICLE PATH MODE – SECOND EVALUATION

gains were also added to the background presentation (ground plane, horizon, and sky plane). These were: 4:1 in the horizontal plane and 2:1 in the vertical plane. These lesser values were used so as not to restrict excessively the field of view represented by the display screen width and height. The final relationships between display view angles and gains are illustrated in Figure II-A-1 of Appendix II-A.

Thrust initiation and termination commands via velocity markers, to the left of the Nominal Path, were the same as in the First Evaluation.

Vehicle altitude and lateral position errors with respect to the Nominal Path were displayed in the same manner as during the First Evaluation when operating single-scale. Single-scale denotes a single range of ± 100,000 feet in both altitude and lateral position error using one configuration of the Nominal Path. Vehicle position errors being displayed by a reduction in path width for increasing altitude error and a lateral displacement of the path, in the appropriate direction, for lateral errors as described in Section 2.3.2(1)(a). This was the prime configuration evaluated.

Since vehicle closure with the Nominal Path was a critical flight cue the simulation setup included an additional three-scale presentation configuration to determine if there was value in such a format in improving flight performance. Each scale configuration of the Nominal Path operated in the same manner as described in the preceding paragraph. However, an additional coding feature was added to distinguish between the scale ranges. This coding was dictated by the capability of the available equipment and does not represent optimization from the human engineering viewpoint.

Scale coding was as follows:

VEHICLE ALTITUDE	± 100,000 ft.	Dim path
	± 50,000 ft.	Medium bright path
	± 10,000 ft.	Bright path
VEHICLE LATERAL POSITION	± 100,000 ft.	No tar strips on path
	± 50,000 ft.	Tar strips stationary
	± 10,000 ft.	Tar strips moving

When operating in the three-scale mode, vehicle altitude and lateral positional errors dictated the coding, width and position of the Nominal Path. As either error was reduced, and the vehicle entered the next lower scale range, the coding would change automatically and the Nominal Path width and position would reflect the extreme range position of that particular scale (narrowing and lateral displacement of path as applicable).

(2) Horizontal Display

The horizontal display was simplified by the deletion of the numerical backup data and the required vehicle path heading line from the configuration used in the First Evaluation. The resulting format is shown in Figure 35. This one configuration was used with both the Attitude and Path Modes of the vertical display. The presentation of the space vehicle position corresponded with that of the vertical display when in single-scale or three-scale modes. When in three-scale mode, scale change was reflected by a displacement in vehicle position concurrently with the displacement of the Nominal Path on the vertical display.

(3) Task Loading Switches

The task loading response procedure was improved by eliminating the need for direct extinguishing of the CAUTION light. This unit is located on the right side of the main display panel and in the First Evaluation either use of the left hand (arm obscured the horizontal display) or the right hand (required release of the side-arm controller) was needed to cancel the CAUTION light when this was the correct response. In the Second Evaluation the CLEAR switch on the left side of the display panel was used for this purpose. All other task loading functions remained the same as described in Section 2.3.2(11).

3.3.2 Hybrid Computation Setup

The hardware of the computation setup was essentially the same as described in Section 2.3.4 with the exception that the character generator and related cathode ray tube associated with the generation of digital data for the First Evaluation were deleted (Figure 15).

3.3.2.1 Data Recording

Data recording was essentially the same as described in Section 2.3.4.1 except for some revisions in the parameters recorded. The revised digital printout format is shown in Figure 36.

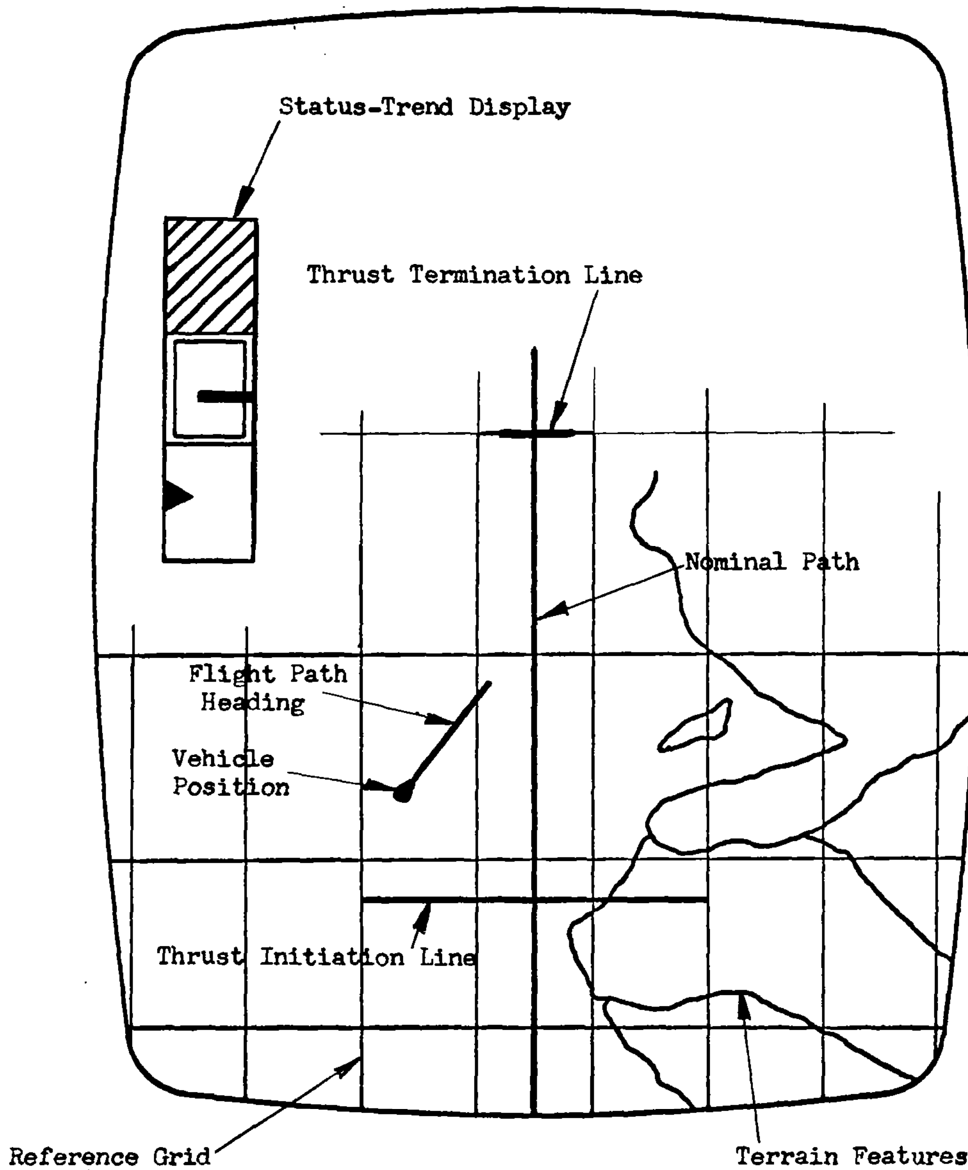


FIGURE 35 HORIZONTAL DISPLAY PRESENTATION - SECOND EVALUATION

1. Elapsed Time t (SEC)	2. Orbital Velocity V (FPS)	3. Altitude h (FT)	4. Actual Flight Path Elevation γ (DEG)	5. Flight Path Heading ψ_H (DEG)	6. Orbital Longitude $\textcircled{Y}_{RP}$ (DEG)	7. Orbital Latitude $\textcircled{Z}_{RO}$ (DEG)	8. Thrust/ Mass Ratio T/M
9. Control Mode & Display Mode	10. Present Yaw ψ_3 (DEG)	11. Present Pitch θ_3 (DEG)	12. Present Roll ϕ_3 (DEG)	13. Reference Pitch Angle θ_{REF} (DEG)	14. Display Velocity Error V_E (FPS)	15. Elev. of Nominal Path from Horiz. γ_{NOM} (DEG)	16. Nominal Insertion Velocity V_{NOM} (FPS)
17. Yaw Error ψ_E (DEG)	18. Pitch Error θ_E (DEG)	19. Nominal Path Altitude h_{NOM} (FT)	20. Lateral Vehicle Displacement Y_P (FT)	21. Distance to Thrust Termination Z_P (FT)	22. Lateral Velocity $\dot{Y}_o$ (FPS)	23. Total Thrusting Time Δt_B (SEC)	24. Velocity Change ΔV (FPS)
25. Energy Expended Roll Δp_s (DEG/SEC)	26. Energy Expended Pitch Δq_s (DEG/SEC)	27. Energy Expended Yaw Δr_s (DEG/SEC)	28. Velocity Error ϵ_V (FPS)	29. Flight Path Elev. Error ϵ_γ (DEG)	30. Altitude Error Δh (FT)	31. Pitch Acceleration $\Delta \dot{q}_E$ (DEG /SEC^2)	32. Yaw Acceleration $\Delta \dot{r}_E$ (DEG/SEC^2)

FIGURE 36 DIGITAL PRINTOUT FORMAT - SECOND EVALUATION

3.4 SUBJECTS

3.4.1 Selection and Grouping

The pilot-subjects employed in the Second Evaluation were LTV engineers and Navy BuWeps personnel who were known to have extensive pilot experience. Experienced pilots were employed to minimize training time and to insure homogenuity of the pilot population.

Criteria for selection were identical to those employed in the First Evaluation with one exception. Four subjects, (1, 4, 5, and 6) were the same subjects employed in the First Evaluation. Scheduling problems necessitated the substitution of two subjects. A Navy BuWeps pilot of comparable flight experience was substituted for Subject 2 of the First Evaluation, also a Navy BuWeps pilot. The substitution for Subject 3 was an experiences simulation engineer who lacked the flight experience of the other subjects, but who was highly experienced in simulation flight proceudres. (This subject was subsequently found to fly the best injection maneuver.)

Pilot subjects were employed to permit generalization to the astronaut population. However, uniform skill levels across subjects were not as critical as for the First Evaluation because each subject was compared with his own performance under different conditions. In the First Evaluation, three pilots were assigned to one treatment (display gain) and three pilots were assigned to another (variable gain), hence, homogenuity of pilot experience was necessary to insure that differences between treatments were not due to differences in skill. In the Second Evaluation, each pilot-subject served as his own control; the same subject was compared under two different treatments. Sequence effects of treatments were minimized by assigning treatment A first for three subjects and treatment B first for the other three subjects. Hence, difference in performance between treatments are not due to basic skill differences between subjects or sequence effects, and, therefore, should be due to differences in treatments, e.g. display characteristics.

3.4.2 Evaluative Subjects

A number of engineering shakedown flights were made prior to the beginning of the formal experimental test period. Participants were the MAFS Group Supervisor and the Project Engineer for this study. These flights were conducted to establish the level of difficulty of the proposed simulation task and to determine easily programmed methods for improving the presentation to the subjects. The decision to increase the gain setting on the tip of the path was a product of the shakedown flights.

In addition, each morning prior to running the subjects, the simulator displays were calibrated to insure that they were uniform in the presentation of information. The MAFS Group Supervisor assisted by the Safety Engineer participated in the calibration.

3.5 PROCEDURE

3.5.1 Independent Variables

The independent variables of interest in the Second Evaluation were as follows:

(1) Vertical Display Characteristics and Interpretation - This variable was uniform throughout the Second Evaluation; however, injection point data acquired during the Second Evaluation will be compared with comparable injection point data for the First Evaluation. In this sense, the revised display setup may be compared to a control condition, the display setup employed in the First Evaluation, and tests of significance will be conducted to determine the probability of such differences occurring by chance.

In the First Evaluation, pilots were instructed to follow a command attitude profile as depicted by movement of the flight path. The view forward, from the pilot's eyes to the center of the screen, was the direction the space vehicle was pointed. In the Second Evaluation, the pathway represents the nominal path to be achieved and the view forward was the direction the vehicle was moving (the vehicle's flight path or velocity vector). The position of the tip of the path with respect to the center of the display represents elevation and heading (angle) error rather than command attitude information.

This primary difference in display interpretation was a major subject for investigation. In the Path Mode, the pilot no longer received vehicle attitude information, but rather saw the results of his attitude inputs in changes in the vehicle's path relative to the nominal path.

(2) Three-Scales Versus Single-Scale Positional Cues - Each pilot flew seven flights under each of two scale coding conditions. The three-scale coding condition (Section 3.3.1) provided distinct visual cues whenever the pilot reduced his attitude or lateral error below specified distances. At 50,000 feet altitude error, the flight path changed from dim to medium brightness and narrowed to minimum width; and at 10,000 feet it changed again to very bright and minimum width. Similarly, as lateral error was reduced below 50,000 feet, tar strips appeared across the pathway, and at 10,000 feet error the tar strips began to move rapidly. Concurrent with the tar strip changes were lateral displacements of the path. The path was initially at a position of maximum error, but as error decreased the path moved inward toward a centerline position, where the tar strips changed the path displaced outward to a position of maximum error, and again moved inward with decreasing error. The cues were intended to provide greater sensitivity to positional errors. The single-scale condition presented a bright pathway with moving tar strips throughout the flight.

To insure that sequence effects (practice, boredom, etc.) did not confound the data, three subjects received the multiple scale condition first and three subjects received the one scale condition first.

(3) On Path Versus Off Path Initial Conditions - The initial conditions employed in the Second Evaluation were identical to those depicted in Table 4 of the First Evaluation. In order to compare performance under the two types

of conditions, each pilot received seven flights under Initial Condition #1 (on-path) and seven flights under other Initial Conditions #2 through #15 (off-path). Three pilots received the odd numbered initial conditions and three pilots received the even numbered initial conditions.

The Second Evaluation employed a single attitude control mode (Rate control) and the same three axis side-arm controller. The gain in the flight path tip was constant for all conditions. Pilots received no digital information during the Second Evaluation and the systems management tapes were randomly assigned to conditions.

3.5.2 Measurements

Principal performance data were obtained throught the ASI-2100 digital computer typewriter printer. This device printed out 32 flight parameters at the moment of engine shutoff (coded SEN). The data reported in this document are derived from the SEN printouts. Other data collected as backup information were digital printouts every twenty seconds of the same flight parameters and Brush Oscillograph recordings of pilot pitch, roll, yaw, inputs, trim knob displacement, thrust initiation and cutoff times, and task loading initiation and response time. A most useful source of information during the administration of the flights was the X-Y-Z plotter which recorded vehicle position.

3.5.3 Pilot Questionnaire

All simulation pilots were given a brief questionnaire or pilot report upon completion of their flights in the simulator. Most of the questions were ratings on a three point scale; some were short answers. Pilots were provided an opportunity to comment on the displays, controls, or simulation procedure at the end of the questionnaire. The questionnaire with pilot responses and evaluation is presented in Appendix II-C. An analysis of the questionnaire data is presented in Section 3.6.3.

3.5.4 Pretraining

All subjects were interviewed ten days before initiation of the simulation. Each subject received a Pilot Handbook, similar to that provided for the First Evaluation, which described the simulated vehicles characteristics, the flight plan, the displays and controls available and their functions, and the flight management procedure. The major differences between the experimental setup for the First and Second Evaluation were verbally described to the pilots. The pilots were told that they would fly the cisplanetary injection maneuver under both three-scale and one-scale conditions.

The first day for each subject was designated as the Familiarization Day and was so recorded in the Flight Log. Subjects were given a short briefing and were given an opportunity to ask questions. They were then seated in the MAFS gondola, briefed on flight procedures by the Simulation Engineer, and were given safety instructions in the event the simulator malfunctioned.

The first two flights were conducted in the automatic mode. The flight profile was managed by the computer, the only pilot tasks being to initiate and terminate thrust, and monitor the systems status displays. One of the automatic flights was Initial Condition #1 (on-path); another automatic flight was an extreme off-path condition, e.g., Initial Condition #12 (15.1 miles left of plane and 33.3 miles above nominal altitude).

Following the automatic flight the pilot was given a manual flight. The first four runs were conducted without the systems monitoring task to enable the pilot to devote full time to flight management. Pilots received at least nine familiarization flights beginning with the simpler initial conditions (1, 2, and 3) and progressing to the more difficult, off path initial conditions. Most of the flights were with the three- scale condition. The pilot's skill in mastery of the flight management task was used to gauge when to stop the familiarization period. At the end of the first day, all pilots appeared to have mastered the rudiments of the flight task and were transitioned to the experimental sequence.

3.5.5 Experimental Procedure

All experimental flights were conducted in the same manner for all subjects. Name, date and flight number was recorded on the digital readout sheets, the strip chart oscillograph tapes, and the X-Y plotter graphs. Computer personnel were given the predetermined I.C. number, scale mode, and task load number before each flight.

The pilot was asked whether he was ready to go. At the same time the MAFS Safety Engineer signified the readiness of the simulator. The pilot was then instructed to select the "Start Program" at will. The pilot established a null orientation to local vertical and the vehicle's orbital path vector. The pilot was then asked to estimate his position with respect to the nominal path as depicted by the position of the Nominal Path on the Vertical Display. His response was recorded in the Simulation Log and he was advised on the correctness of his estimate.

After approximately four minutes in the ATTITUDE mode, the pilot was informed that it was 90 seconds until thrust initiation and that he should arm his thrust control by pressing the THRUST and NUCLEAR PROPULSION push buttons. Shortly thereafter he was to select his PATH mode display. The path display represented the required path that the pilot was to acquire (if off path) and maintain in order to arrive at the cisplanetary injection point.

Thrust initiation time was indicated by the pulsing of the velocity markers followed by the markers disappearing momentarily, then reappearing and moving away rapidly. Thrust ignition was accomplished by moving the thrust lever forward.

During the PATH mode, communications with the pilot were kept to a minimum while he regulated his attitude controller and set up a program for achieving the nominal path. After thruster cutoff, the pilot was asked to select STOP PROGRAM (which reset the computer), to disarm the thruster control, and to select ATTITUDE mode on the displays.

The Test Conductor reported to the subject after each flight his flight path elevation and heading errors and his lateral, altitude, and velocity errors. This data was read from the typewriter printout record which was made at the instant of engine shutoff (SEN).

Each flight required approximately fifteen minutes. There were rest periods of two to five minutes between flights and a 15 - minute break after an hour to an hour and one half.

Upon completion of the formal testing period, which included two experimental sessions, each subject was given the questionnaire described in Section 3.5.3.

3.5.6 Simulation Flight Log

During the experimental, familiarization, and shakedown flights, a simulation log was maintained by the Test Conductor. The log format was very similar to that reported for the First Evaluation (Section 2.5.6). The Test Conductor prepared in advance an assignment of initial conditions and scale ordering for each subject. These assignments were typed in the Log and dictated the sequence of administration of conditions. The subject assignments are reported in Appendix II-B. Pilot performance (the five SEN readings given to the pilot) was recorded in the log after each trial. Pilot comments and initial condition interpretations were also recorded.

3.6 RESULTS

The two major sources of data for the Second Evaluation were the flight performance (end point) data and the pilot questionnaire.

The results of the Second Evaluation in terms of parametric scores which are summarized by measures of central tendancy across subjects and conditions are given in Section 3.6.1.

The results of the non-parametric test (Mann-Whitney "U" Test) to determine whether the derived differences across conditions could be due to chance or whether there is a high probability that the differences are due to experimental conditions are given in Section 3.6.2.

An analysis of questionnaire results is given in Section 3.6.3.

3.6.1 Injection Point Data Analysis

Of the printout data identified in Figure 36, nine injection point parameters were identified as relevant for evaluating systems performance. These were: flight path errors (elevation, heading, velocity), positional errors (lateral, longitude, altitude), and control energy expenditure (pitch, yaw, roll). These parameters are the same as those measured in the First Evaluation thereby permitting comparison between the two evaluations. A descriptive (graphic) comparison is presented in this section. A statistical comparison and interpretation of data is presented in Section 4.0.

Table 9 summarizes the results of the Second Evaluation in terms of total absolute scores for all subjects, the associated mean values, and the separately calculated median values for each of the nine parameters. Within each of these major summary categories shown in Column 1 are presented the sub-categories of interest: three-scale versus one-scale and on-path initial conditions versus off-path initial conditions.

The measures presented in Table 9 were derived in the following manner:

(1) Scores for each experimental flight were transcribed from the typewritten digital printout records on to (subject) x (flight) matrices. This raw score data for each subject during 14 flights is presented in Appendix II-B.

(2) On each matrix, the scores were summed over flights for each subject. By summing these totals across subjects, a Grand Total was derived for each of the parameters based on 84 measurements. The Grand Mean for each cell was derived by dividing by 84.

(3) The three-scale totals and one-scale totals were derived in a similar manner from raw score data in Appendix II-B by inclusion of only the seven relevant flights per subject. Three-scale means and one-scale means were derived by dividing by 42. The totals and means for on-path (I.C. #1) and off-path (I.C. #2 through 15) were derived in a similar manner.

(4) The grand median, above and below which 50% of the scores lie, was calculated by ranking the 84 scores and assessing a value midway between the 42 and 43 scores. Three-scale and one-scale medians (and on and off path medians) are, by definition, values midway between the 21 and 22 value when the 42 scores are ranked in absolute magnitude.

The median scores are considered to be more representative of the distribution than are the mean scores due to the extreme skew of the distribution of scores. Appendix II-B data shows that a majority of the scores are quite small with a few values often accounting for more than half of the column total. The mean is sensitive to score magnitude; the median is sensitive to ranking only. The effect of using median data is to eliminate the bias of extreme scores and, when the extreme scores are very large, to make the median smaller than the mean.

Figures 37 through 45 present by histogram the median data presented in Table 9 in order to clarify the effects of experimental conditions on particular parameters. The reader can readily assess from Columns 2 through 6 which conditions are contributing to increasing the grand median (Column 1) and which are reducing the median. Columns 7, 8, and 9 present comparable data from the First Evaluation (maximum, minimum, and median values for the eight conditions). These results are discussed in Section 3.6.1.1.

The data presented in Table 9 and illustrated in Figures 37 through 45 presents three-scale versus one-scale data with initial flight conditions grouped together and on-path versus off-path initial conditions with the three scale and one scale data grouped together. Each of the four presentations was based on 42 data points. However, in order to determine which single condition resulted in the best overall performance, the data was further analyzed as follows:

(1) On-path initial conditions with three-scale and one-scale data analyzed separately.

(2) Off-path initial conditions with three-scale and one-scale data analyzed separately.

It was hypothesized that the best performance would be achieved during the on-path condition for whichever scale variable was determined to be superior. Table 10 summarizes the results of this analysis. Each of the medians was based on 21 data points.

MEASUREMENT	INITIAL COND.	SCALES	FLIGHT PATH ERRORS: ELEV. ϵ_γ DEG.	HEAD ψ_H DEG.	VEL. ϵ_V FPS	POSITION ERRORS: LATERAL Y_P FT	LONG Z_P FT	ALT. Δh FT	CONTROL ENERGY EXPENDITURE: PITCH %	YAW %	ROLL %
GRAND TOTAL	ALL	1,3	50.055	20.736	48,644.3	949,999	428,393	1257253	1,441.87	1063.03	836.70
3-SCALE TOTAL	ALL	3	29.393	15.755	29,940.8	546,393	263,130	546521	797.43	581.16	471.44
1-SCALE TOTAL	ALL	1	20.662	4.981	18,703.5	403,606	165,263	710732	644.44	481.87	365.26
ON-PATH TOTAL	#1	1,3	20.672	6.793	26,815.4	172,940	157,779	427097	670.29	429.95	332.82
OFF-PATH TOTAL	#2 THRU #15	1,3	29.383	13.943	21,828.9	777,059	270,614	830156	771.58	633.08	503.88
GRAND MEAN	ALL	1,3	0.596	0.247	579.0	11,309	5,224	14,966	17.58	12.96	10.20
3-SCALE MEAN	ALL	3	0.700	0.375	712.8	13,009	6,265	13,010	18.98	13.84	11.22
1-SCALE MEAN	ALL	1	0.492	0.119	445.3	9,610	4,132	16,922	16.11	12.05	9.13
ON-PATH MEAN	#1	1,3	0.492	0.162	638.4	4,117	3,754	10,168	16.34	10.48	8.11
OFF-PATH MEAN	#2 THRU #15	1,3	0.700	0.332	519.7	18,501	6,424	19,765	18.81	15.44	12.28
GRAND MEDIAN	ALL	1,3	0.305	0.032	11.7	2,488	2,799	6,560	16.12	11.75	9.62
3-SCALE MEDIAN	ALL	3	0.596	0.247	12.9	1,154	3,711	4,079	18.49	12.59	10.08
1-SCALE MEDIAN	ALL	1	0.284	0.017	9.4	4,259	2,029	7,626	15.05	10.15	9.20
ON-PATH MEDIAN	#1	1,3	0.208	0.021	11.5	1,262	1,880	4,875	15.09	9.93	6.86
OFF-PATH MEDIAN	#2 THRU #15	1,3	0.416	0.051	12.6	7,743	4,655	9,879	16.81	15.04	11.05

TABLE 9

SUMMARY OF SECOND EVALUATION PERFORMANCE

On-Path vs Off-Path, with One and Three-Scales Grouped
One-Scale vs Three-Scale, with On and Off-Path Grouped

Figure 37 - Median Flight Path Elevation Error

Of the four major conditions investigated, the on-path initial condition resulted in the most accurate elevation angle at injection (.208 degrees) followed by one-scale, off-path, and three-scale in that order. On-path, single-scale resulted in the best sub-condition, but only slightly better than the on-path with combined single and three-scales. Although the error is 20 times as great as the largest error reported for the First Evaluation, it is submitted that an accuracy of 12 minutes or .2 of one degree may well be satisfactory for a cisplanetary injection with subsequent midcourse corrections.

Figure 38 - Median Flight Path Heading Error

Of the four major conditions, the one-scale and on-path initial conditions resulted in the smallest heading error followed by the off-path condition. The three-scale condition resulted in five or more times as great an error as any of the other three conditions. The on-path, single-scale condition resulted in a median error of .009 degrees which is smaller than the maximum for the First Evaluation (.015) and comparable to the median (.003). This accuracy is well within requirements for an orbital injection.

Figure 39 - Median Velocity Error

The one-scale condition incurred the smallest median velocity error followed by on-path, off-path, and three-scale conditions in that order. The on-path, single-scale condition of 7.3 feet per second was comparable to the 5.0 fps median reported for the First Evaluation. Velocity error was primarily due to terminating late (at a velocity in excess of 42,000 feet per second) and is probably more a function of attention to the velocity marker than to other display characteristics. The high three-scale error suggests lack of control during the terminal thrust period.

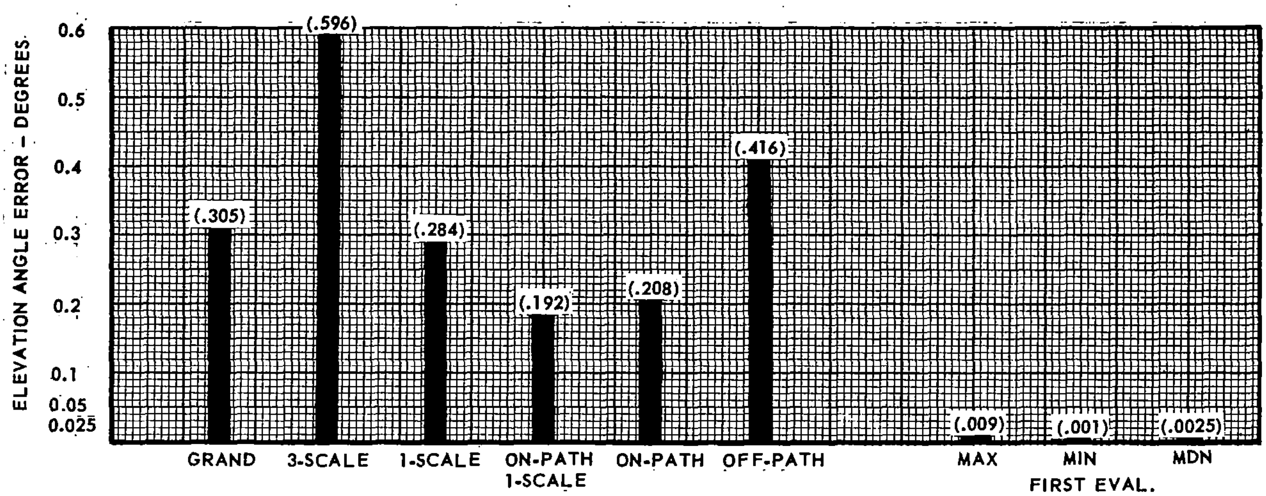


FIGURE 37 MEDIAN FLIGHT PATH ELEVATION (ANGLE) ERROR – SECOND EVALUATION

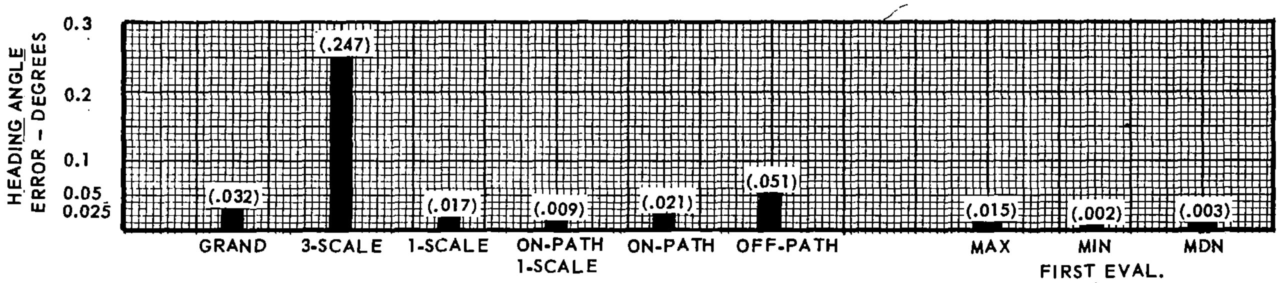


FIGURE 38 MEDIAN FLIGHT PATH HEADING (ANGLE) ERROR – SECOND EVALUATION

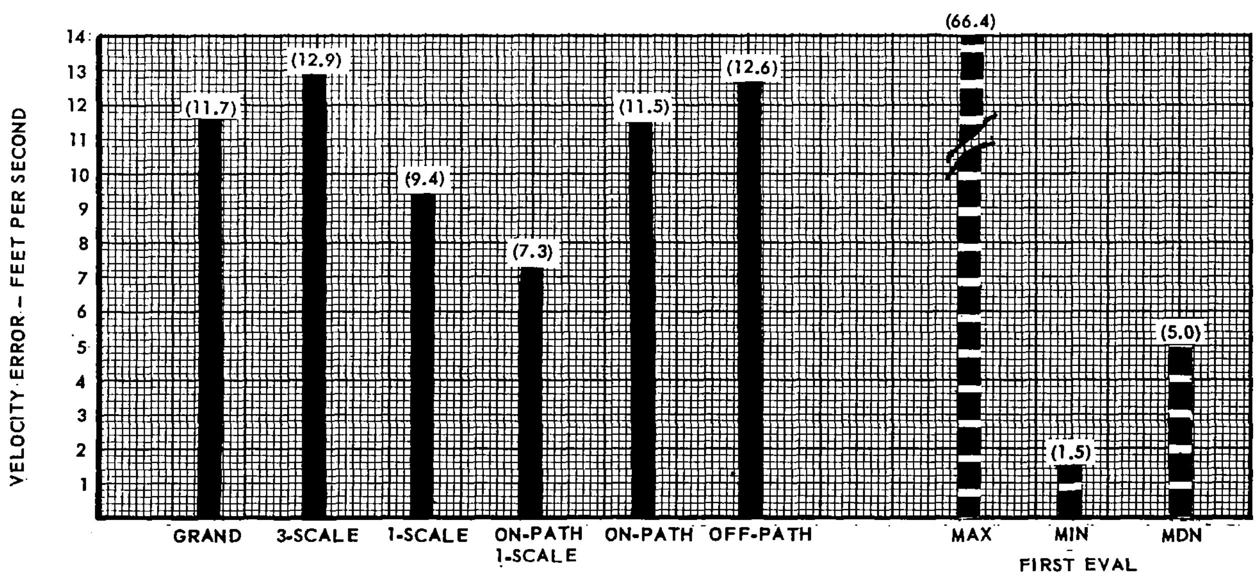


FIGURE 39 MEDIAN VELOCITY ERROR AT INJECTION – SECOND EVALUATION

Figure 40 - Median Lateral Error

The three-scale condition resulted in the smallest error followed closely by the on-path condition. The one-scale error was nearly four times as great and the off-path error was seven times as great. It is suggested that scale changing magnifies the importance of position error. Three-scale, on-path error is only slightly more than 1,000 feet and easily corrected for during the cisplanetary flight.

Figure 41 - Median Longitudinal Error

The on-path initial condition resulted in the smallest longitudinal error at injection with the one-scale condition only slightly less accurate. The three-scale and off-path conditions resulted in median errors approximately twice as large. Eight-eight per cent of the errors were positive signifying a late termination. Late termination is most likely a function of attention to velocity markers during the terminal thrust period. Longitudinal error was significantly smaller for the Second Evaluation than for the First Evaluation. The best single sub-condition was on-path, single-scale (1,181 fps).

Figure 42 - Median Altitude Error

The three-scale condition resulted in smaller median error than the one-scale condition; however, the differences were not significant according to the Mann-Whitney "U" Test (see Section 3.6.2). The on-path, one-scale, and off-path conditions followed in that order. Median altitude errors were significantly larger than those reported for the First Evaluation. Altitude error is the only parameter where the grouped on and off path error value was smaller than errors for the on-path condition only.

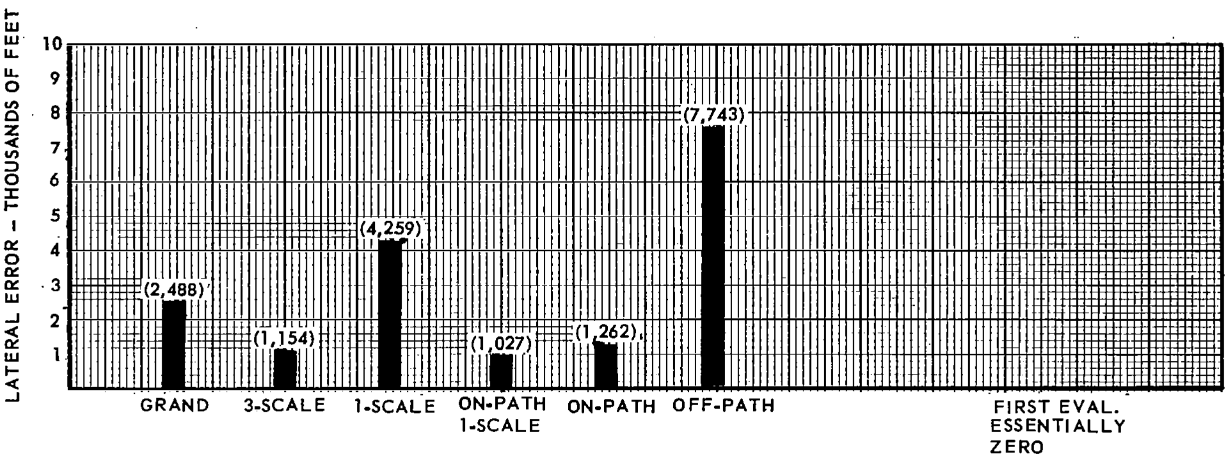


FIGURE 40 MEDIAN LATERAL ERROR AT INJECTION – SECOND EVALUATION

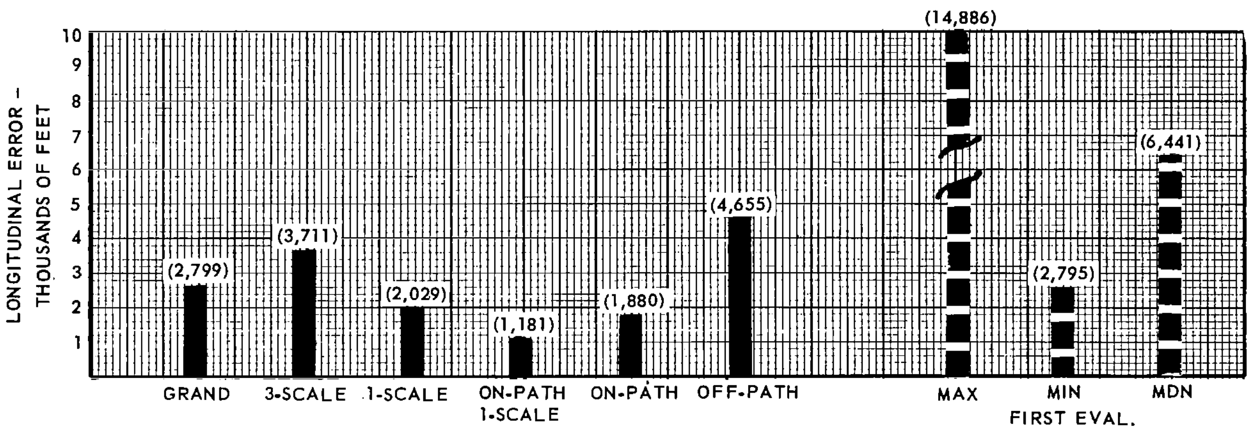


FIGURE 41 MEDIAN LONGITUDINAL ERROR AT INJECTION – SECOND EVALUATION

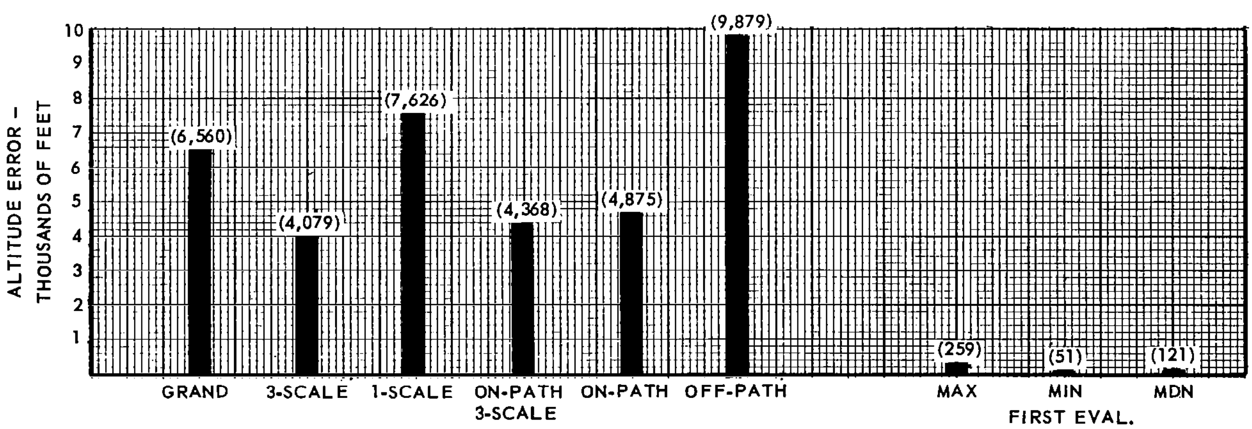


FIGURE 42 MEDIAN ALTITUDE ERROR AT INJECTION – SECOND EVALUATION

Figure 43 - Median Pitch Energy Expended

Pitch, yaw, and roll were much less affected by experimental conditions than were flight path and position errors, i.e., the percent of total energy expended was more or less homogeneous across conditions, ranging from 15% to 18% for pitch. The on-path, single-scale condition at 13.68% was the best single sub-condition or condition. Pitch energy expenditure was significantly lower than that for the First Evaluation. It is suggested that in the First Evaluation pilots tended to compensate for minor errors from command attitude resulting in a somewhat wasteful expenditure of energy. In the Second Evaluation, scale sensitivity was less at large error initial conditions, and once a vehicle path closure with the Nominal Path was set up the pilot applied minimal control inputs until close proximity to the Nominal Path was achieved.

Figure 44 - Median Yaw Energy Expended

Yaw energy expenditure ranged from approximately 10% to 15% for the four major conditions. The on-path, single-scale condition at 8.28% was the best single sub-condition or condition. Yaw energy expenditure was also significantly lower for the Second Evaluation than for the First Evaluation for the same reasons suggested in the preceding paragraph.

Figure 45.- Median Roll Energy Expended

Roll energy expenditure ranged from approximately 7% to 11% for the four major conditions. The on-path, single-scale condition at 5.48% was the best single sub-condition or condition. The median roll energy expenditure for the First Evaluation is significantly lower than median roll expenditure for the Second Evaluation. However, the on-path, single-scale median does not differ appreciably from the First Evaluation median of 4.6%.

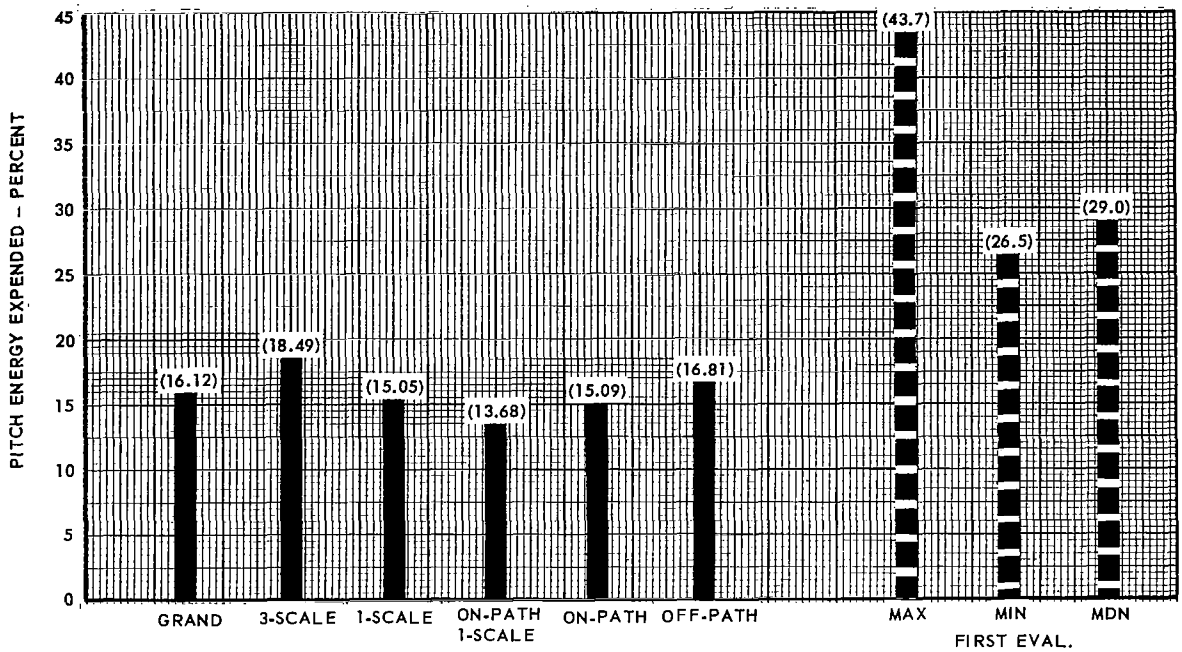


FIGURE 43 MEDIAN PITCH ENERGY EXPENDED – SECOND EVALUATION

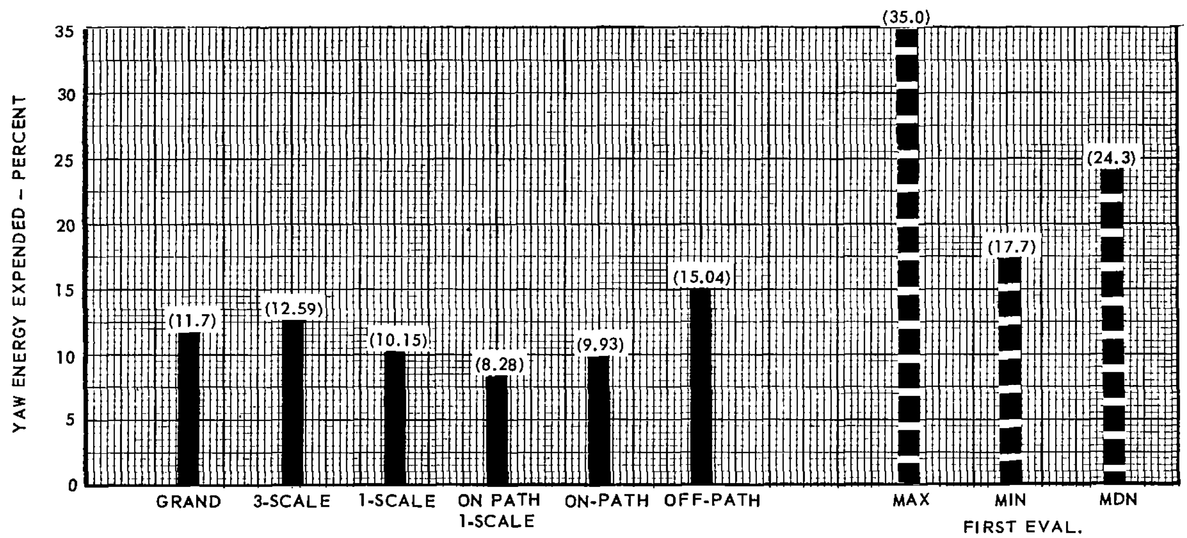


FIGURE 44 MEDIAN YAW ENERGY EXPENDED – SECOND EVALUATION

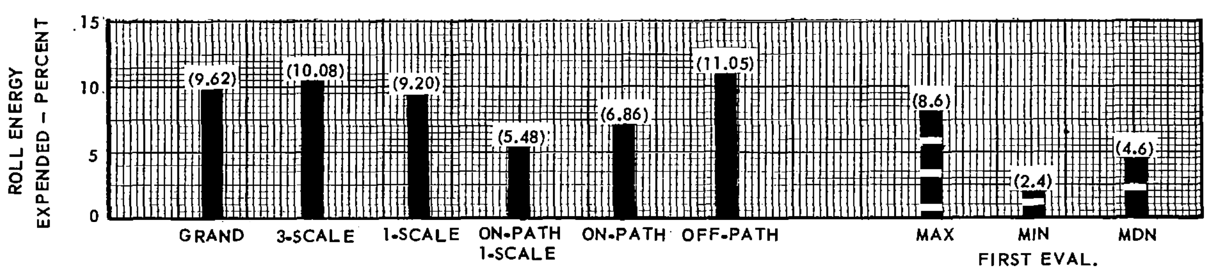


FIGURE 45 MEDIAN ROLL ENERGY EXPENDED – SECOND EVALUATION

	FLIGHTS	INITIAL COND.	SCALES	FLIGHT PATH ERRORS ELEV. ϵ_γ DEG.	HEAD. ψ_H DEG.	VEL. ϵ_V FPS	POSITION ERRORS LATERAL Y_P FT	LONG. Z_P FT	ALT. Δh FT	CONTROL ENERGY EXPENDITURE PITCH %	YAW %	ROLL %
	ON PATH	- SINGLE	SCALE									
MEANS	20	1	1	.358	.125	899	4,798	2,420	10,200	13.90	9.45	6.44
MEDIANS	20	**1**	**1**	**.192**	**.009**	**7.35**	**2,704**	**1,181**	**4,593**	**13.68**	**8.28**	**5.48**
	ON PATH	- THREE	SCALE									
MEANS	22	1	3	.589	.191	429.3	3,499	4,971	10,138	18.46	11.38	9.56
MEDIANS	22	**1**	**3**	.265	.038	12.5	**1,027**	2,681	**4,368**	18.00	11.05	9.40
	OFF PATH	- SINGLE	SCALE									
MEANS	22	2-15	1	.605	.109	60.6	13,984	5,311	23,030	18.11	14.40	11.56
MEDIANS	22	2-15	1	.306	.028	11.7	9,438	3,513	12,484	15.88	14.88	10.67
	OFF PATH	- THREE	SCALE									
MEANS	20	2-15	3	.803	.576	1,025	23,471	7,688	16,174	19.56	16.54	13.05
MEDIANS	20	2-15	3	.552	.062	19.8	1,919	5,174	8,022	19.38	15.55	12.81
	SUMMARY											
MEANS	84	1-15	1&3	.588	.250	604	11,438	5,098	14,886	17.51	12.94	10.15
MEDIANS	84	1-15	1&3	.286	.033	12.10	2,314	3,097	6,194	16.94	12.97	10.04

▭ -Best Performance (boxed values shown in bold)

TABLE 10

SUMMARY OF SECOND EVALUATION PERFORMANCE

On-Path vs Off-Path with One-Scale and Three-Scale Data Analyzed Separately

3.6.1.1 Discussion of End Point Data Results

(1) General Observations

(a) First Evaluation median performance was superior to the Second Evaluation on all parameters except longitudinal error, pitch energy expended, and yaw energy expended.

(b) The Second Evaluation has demonstrated that a pilot with a minimum of training can perform a successful cisplanetary injection maneuver with the displays provided. (Median end point performance was comparable to presently available requirements for Apollo and interplanetary flight.)

(c) Performance with initial "on-path" initial conditions were superior to "off-path" initial conditions on all nine parameters.

(d) Performance at injection point is superior with a single-scale than with a three-scale on all parameters except lateral and altitude position errors. Apparently, the greater positional accuracy available in three-scale operation encourages the pilots to concentrate more on minimizing position errors. While under single-scale conditions positional errors were less obvious and pilots concentrated on the more significant factor, minimizing elevation and heading angles.

(e) The on-path, single-scale condition resulted in the best overall performance on all parameters except lateral position error.

(2) Comparative Performance on Individual Parameters

Under all conditions, heading error (Figure 38) was less than elevation error (Figure 37) and lateral position error (Figure 40) was less than altitude position error (Figure 42). There are several possible explanations for the superior lateral control:

(a) The larger gain in the path for heading error (32:1) than for elevation error (6:1) resulting in more discernible lateral movement of the tip.

(b) A more positive indication when the vehicle was on Nominal Path (centered) than when nominal altitude had been achieved (apparent view from above or below).

(c) Redundant information in the horizontal display.

(d) More deviant initial conditions in altitude than lateral error under some conditions.

3.6.2 Mann-Whitney "U" Test

The Mann-Whitney "U" Test was applied to median score data for the Second Evaluation in order to determine the statistical significance of the differences reported, i.e., to determine the probability that such differences might have occurred by chance.

The nine relevant parameters were compared under the following conditions discussed in Section 3.6.1:

(1) On-Path versus Off-Path.

(2) Three-Scale versus One-Scale, with On-Path and Off-Path conditions combined.

(3) Three-Scale versus One-Scale, considering only On-Path conditions. In addition, the grand median scores for the Second Evaluation were compared with those for the First Evaluation. The results of the Mann-Whitney test as applied to the comparison between the First and Second Evaluations will be discussed in Section 4.0.

Tables 11, 12, and 13 summarize the results of the three comparisons. For each of the parameters, the median scores are shown for the two conditions being compared. The fourth column reports the level of significance of the difference as determined by the Mann-Whitney Test. If the probability of difference between the two medians occurring by chance is greater than 20%, the difference is considered non-significant (N.S.). This implies that we cannot be too confident that there is a real difference between the two groups because the reported difference could occur as often as 20% of the time by chance. The last column indicates which condition had the smaller error or superior performance. If the difference is not significant, no trend is indicated.

The test of significance was conducted in the following manner:

(a) Reference was made to the raw score data (Appendix II-B). For each subject and each parameter, there are seven raw scores for each of the conditions, i.e., seven three-scale, seven one-scale, seven initial conditions #1 (on-path) and seven initial conditions #2 through #15 (off-path). The median (fourth ranking score) was determined for each of the six pilot subjects. (See illustration below.)

(b) In comparing two conditions, the six median scores from each were combined and ranked from smallest error to largest error. Opposite each score was indicated the original identity of the median before combination.

(c) The "U" Test is based on the assumption that a highly significant difference between conditions would be one in which all the median scores from one condition are ranked above (or below) all the median scores from the other group. To the degree there is overlap in the joint rankings, the probability of a real difference is lower. To determine "U" for small groups, Siegel (Reference 9) requires a simple counting of the number of times a member of Group B precedes a member of Group A as illustrated below. The count column is summed yielding a "U" value and reference is made to Tables in Siegel listing the level of significance for the "U" for a 6 by 6 subject comparison.

ILLUSTRATION OF PROCEDURE FOR CALCULATING "U" VALUES
FOR SMALL GROUPS HEADING ERROR

SUBJECT	MEDIAN SCORES		JOINT RANKINGS	CONDITION	COUNT	
			.006	3		
	3 Scale	1 Scale	.009	1	1	U = 9
			.009	1	1	
1	1.658	.027	.011	1	1	Significant at
2	.024	.011	.024	3		.090 level
3	.006	.009	.026	1	2	
4	.126	.034	.027	1	2	
5	.035	.026	.034	1	2	
6	.164	.009	.035	3		
			.126	3		
			.164	3		
			1.658			

MEASURE	ON-PATH	OFF-PATH	LEVEL*	TREND
FLIGHT PATH ERROR				
ELEVATION	0.208 deg	0.416 deg	0.155	ON-PATH
HEADING	0.021 deg	0.051 deg	0.155	ON-PATH
VELOCITY	11.5 fps	12.6 fps	N.S.(.409)	NONE
POSITION ERRORS				
LATERAL	1,262 ft	7,743 ft	N.S.(.242)	NONE
LONGITUDINAL	1,880 ft	4,655 ft	0.066	ON-PATH
ALTITUDE	4,875 ft	9,879 ft	0.066	ON-PATH
CONTROL ENERGY EXPENDITURE				
PITCH	15.09 %	16.81 %	N.S.(.294)	NONE
YAW	9.93 %	15.04 %	0.013	ON-PATH
ROLL	6.86 %	11.05 %	0.013	ON-PATH

* Level of significance (Mann-Whitney "U" Test)

TABLE 11

A COMPARISON OF ON-PATH VERSUS OFF-PATH

MEDIAN PERFORMANCE AT INJECTION POINT

SECOND EVALUATION

MEASURE	THREE SCALE	ONE SCALE	LEVEL*	TREND
FLIGHT PATH ERROR				
ELEVATION	0.596 deg	0.284 deg	.120	One-Scale
HEADING	0.247 deg	0.017 deg	.090	One-Scale
VELOCITY	12.9 fps	9.4 fps	.155	One-Scale
POSITION ERRORS				
LATERAL	1,154 ft	4,259 ft	.006	Three-Scale
LONGITUDINAL	3,711 ft	2,029 ft	N.S.(.242)	None
ALTITUDE	4,079 ft	7,626 ft	N.S.(.531)	None
CONTROL ENERGY EXPENDITURE				
PITCH	18.49 %	15.05 %	.155	One-Scale
YAW	12.59 %	10.15 %	N.S.(.350)	None
ROLL	10.08 %	9.20 %	N.S.(.294)	None

* Level of significance (Mann-Whitney "U" Test)

TABLE 12

A COMPARISON OF THREE-SCALE VERSUS ONE-SCALE

MEDIAN PERFORMANCE AT INJECTION POINT -

ON-PATH AND OFF-PATH CONDITIONS COMBINED

SECOND EVALUATION

MEASURE	THREE SCALE	ONE SCALE	LEVEL*	TREND
FLIGHT PATH ERROR				
ELEVATION	.589 deg	.192 deg	.197	One-Scale
HEADING	.038 deg	.009 deg	.021	One-Scale
VELOCITY	12.5 fps	7.3 fps	N.S.(.242)	None
POSITION ERRORS				
LATERAL	1,027 ft	2,709 ft	.021	Three-Scale
LONGITUDINAL	2,029 ft	1,181 ft	.120	One-Scale
ALTITUDE	4,368 ft	4,593 ft	N.S.(.409)	None
CONTROL ENERGY EXPENDITURE				
PITCH	18.00 %	13.68 %	.120	One-Scale
YAW	11.05 %	8.28 %	N.S.(.350)	None
ROLL	9.20 %	5.48 %	.120	One-Scale

* Level of significance (Mann-Whitney "U" Test)

TABLE 13

A COMPARISON OF THREE-SCALE VERSUS ONE-SCALE

MEDIAN PERFORMANCE AT INJECTION POINT -

ON-PATH CONDITIONS ONLY

SECOND EVALUATION

3.6.2.1 **Discussion of Mann-Whitney "U" Test Results**

(1) Table 11 indicates that on-path initial conditions resulted in significantly superior performance for six parameters; off-path initial conditions were superior for no parameters; three parameters resulted in non-significant results. The differences between conditions for yaw and roll energy expenditure were highly significant; the difference between conditions for position errors were fairly reliable with a probability of being wrong of less than 7 per cent. Differences between elevation and heading were significant, but at a very low level (.20 or greater was defined as non-significant).

(2) Table 12 presents a comparison of three-scale versus one-scale displays when on-path and off-path conditions were combined. Under these conditions the one-scale was superior on four parameters, the three-scale was superior on one parameter, lateral error. Four parameter differences were not significant.

(3) Table 13 presents a comparison of three-scale and one-scale displays for on-path data only. This comparison was made because it was originally predicted that the on-path condition would result in best performance and it was suspected that some of the differences between three-scale and one-scale reported in Table 12 were obscured by large degradation contributed by off-path initial conditions. By considering only on-path initial conditions the effects of scale factors alone would be manifest favoring the single-scale by greater differences.

Analysis of the data indicated that the effects of considering only on-path initial conditions was to increase the level of significance below .20 for two parameters - longitudinal error and roll control energy expenditure, but also to decrease the level of significance for another, velocity error. The net result was that five parameters were now significant in favor of the single-scale as compared with four parameters when on-path and off-path were combined. However, the predicted overall effect of increasing the differences in medians was not confirmed. Five differences were increased; three differences were decreased; one difference was unchanged.

(4) In summary, the results of the Mann-Whitney Test for significance supports conclusions reported in Section 3.6.1.1. The differences between medians for the single and three-scale conditions are unlikely to have occurred by chance and reflect real differences favoring the single-scale display except for lateral error control. On-path initial conditions also result in significantly better performance than off-path initial conditions.

3.6.3 Questionnaire Analysis

The Pilot Questionnaire was administered to all subjects following their participation in the study. The questionnaire format, the rating scales used, group results, individual ratings and comments are given in Appendix II-C.

The following summarizes the key statements made:

(1) Pilots judged the Second Evaluation Thrust Phase task to be more difficult than the First Evaluation task, but more interesting.

(2) The loss of vehicle attitude information was felt to be a handicap.

(3) The realism of the Vertical Display presentation was equal to that of the First Evaluation.

(4) Nominal path tip (vanish point) displacement with respect to the center of the Vertical Display was the primary cue for estimating vehicle flight path heading and elevation error.

(5) Occasional to considerable confusion was reported due to the inherent slow response of the nominal flight path to flight control inputs, suggesting the need for increased sensitivity or other improvements in this area.

(6) The velocity marker was rated a fairly good cue for thrust initiation and cutoff, but a cue requiring less concentration would be preferred.

(7) The Horizontal Display was used more often than in the First Evaluation as a supplement to the Vertical Display and primarily for vehicle path heading and vehicle position information. A need was expressed for a similar display for flight planning in the vertical plane.

(8) The digital information provided in the First Evaluation was generally not missed. Two pilots requested altitude and lateral error readouts; however, use of more responsive display configurations should minimize the need for this type of information.

(9) Despite the increased difficulty of the Second Evaluation, most of the pilots judged the systems monitoring task to be less distracting than during the First Evaluation. An explanation may be that the monitoring task, as programmed, was too simple.

(10) More time was spent with the flight management task than with the systems monitoring task. During vehicle coast, two thirds as much time was spent monitoring systems as flight management, while during vehicle thrusting only one third as much time was spent monitoring. These differences are most likely due to a coast period with little flight management activity other than vehicle attitude control, and to the added demands of the flight management task during thrusting, respectively.

(11) Opinion was divided on the value of the three scales for achievement of the nominal path. An explanation may be found by reference to the end point data, which revealed that the three scales provided better vehicle lateral and altitude control, whereas the single scale resulted in more accurate elevation and heading angles. An improved scaling technique should incorporate the advantages of both the single and three scale techniques.

(12) Subjects commented that three-scale changing was confusing when errors were large, but were useful when the nominal path had been achieved. They recommended either a two-scale system with manual changeover or eliminating step changes entirely and increasing sensitivity as error is reduced.

(13) Brightness was rated the most helpful cue that a scale had changed.

(14) There was a lack of a positive index of when the nominal altitude has been achieved, i.e., the Vertical Display implementation requires that pilots recognize that nominal altitude is a displayed condition with the sides of the path coincident with the corners of the scope. Further altitude correction results in the path switching abruptly to a similar position in the opposite field (above or below). Pilots frequently used this flipping as a gauge of on-altitude conditions.

(15) Large elevation and heading angles resulted in the path tip moving out of view. This condition could be avoided by a logarithmic decrease in sensitivity of the path tip. For large errors, horizontal and vertical situation planning displays were recommended.

(16) Indication of the rate of change in altitude (path width) was not sufficiently pronounced.

(17) Immediate feedback on the amount of the pilots attitude correction was recommended. This could be achieved by a more sensitive feedback of the effects of attitude changes on flight path and positional errors.

3.6.4 Conclusions and Recommendations

3.6.4.1 Conclusions

(1) General

(a) First Evaluation median performance was superior to the Second Evaluation on six of the nine critical parameters (elevation and heading angles, velocity, lateral position, and altitude errors; and roll energy expenditure). Second Evaluation parameters for which significantly better performance was achieved were longitudinal error, pitch and yaw energy expenditures.

(b) With a minimum of training,pilots were able to perform a successful cisplanetary injection maneuver with the displays provided.

(c) Performance with a single-scale positional error presentation was superior to that with three-scales on five parameters. Superior performance with three-scales was achieved only for lateral error control. Three parameters showed no significant difference. The implication of this finding is that future displays should employ a single-scale modified to provide greater sensitivity for small position errors.

(d) On-path initial conditions resulted in superior performance than off-path initial conditions on six parameters; three parameters reported no significant difference.

(e) Median performance was better in the horizontal plane than in the vertical plane. Heading errors were smaller than elevation errors and lateral position errors were smaller than altitude position errors. Among the factors contributing to better horizontal performance were the higher error display gain used and the existence of a horizontal display for planning purposes.

(f) Significant observations from analysis of the questionnaire data were as follows:

(1) The Second Evaluation was more difficult, but more challenging and interesting due to the increased responsibility assigned to the pilot.

(2) The three-scale condition was considered detrimental and a modified single-scale technique was recommended.

(3) The Horizontal Display was used more often than in the First Evaluation and a comparable vertically oriented presentation was suggested for altitude control when the vehicle is off path at greater than line-of-sight distances.

(4) The absence of vehicle attitude information was considered to be a handicap suggesting the need for greater sensitivity in presenting vehicle position relative to the flight path.

(5) The cue for thrust cutoff (at injection) should be more positive.

(6) Digital information was considered to be unnecessary with the displays provided.

(7) The systems monitoring task was not sufficiently distracting and was too simple for task loading as it was programmed.

(2) Vertical Display Flight Path Heading and Elevation Angle Presentation

The Space Analog Vertical Display was not flyable when the vehicle flight path heading and elevation angles with respect to the required path were presented in true relationship (1:1 with the real world). Display gain in flight path heading error (32:1), and elevation angle error (6:1) resulted in a flyable configuration with the following best median on path performance at the cisplanetary injection point:

Heading error	0.009 degree
Elevation error	0.192 degree

Though the use of fixed gain resulted in acceptable flight performance, it induced undesirable presentation characteristics under certain flight conditions. These were not noticeable when the vehicle flight path heading and elevation errors were relatively small as in a well controlled flight profile. However, they were very pronounced under poor path control and large deviations. Under these conditions, the required path position depicted the amplified error at the expense of its true position to the real world, ie, large path tip displacements above and below the horizon and to the side of the apparent vehicle path.

The gains used provided an adequate presentation of change in elevation and heading errors but the rates of change were still much less than that of a true attitude presentation. Consequently, flight control corrections required care in application.

(3) Vertical Display Vehicle Position Presentation

Flight performance was superior when using a single-scale in presenting vehicle altitude and lateral position errors with respect to the required path. The use of three-scale presentations with increasing sensitivity as the path was approached resulted in undue pilot attention to positional errors at the expense of elevation and heading errors. This is undesirable because the latter are of greater significance to the cisplanetary path required. However, the greater sensitivity of these scales did produce better vehicle positional performance. The results indicate the need for the combination of the best features of single and three-scale presentation of positional errors, i.e., a single path configuration with increasing sensitivity of error presentation as the required path is approached.

Best vehicle position performance was achieved with the ± 10,000 ft. scale as follows:

Lateral error	1,027 feet
Altitude error	4,368 feet

(4) Control System Energy Expenditure

The use of the vehicle attitude control system was significantly less during the Second Evaluation than during the First. In the First Evaluation the command attitude presentation encouraged the constant correction of errors and generally resulted in a certain amount of overcorrection. The Second Evaluation presentation, on the other hand, incorporated a display configuration that required care in control application, as well as flight techniques requiring minimal control action.

Best control system energy expenditure performance was as follows (medians):

	Pitch	Yaw	Roll
On-Path - Single-Scale	13.68%*	8.28%	5.48%
Off-Path - Single-Scale	15.88%	14.88%	10.67%

* Per cent of total available during thrusting period.

3.6.4.2 Recommendations

VERTICAL DISPLAY

(1) Program a Logarithmic Relationship Between Display Sensitivity and Error - Investigate techniques for providing a logarithmic increase in display sensitivity as error is decreased and a logarithmic decrease in sensitivity as error is increased. Parameters affected would include flight path heading, elevation, altitude and lateral errors as displayed on Vertical and Horizontal Displays.

(2) Increase Altitude Error Sensitivity - Increase the sensitivity of the path width to altitude error, i.e., the path should be perceptibly narrower for such initial conditions as 33.3 miles above nominal than for 12.5 miles above nominal. With training, pilots should be able to associate displayed path widths with specific altitude errors. Accuracy in estimating altitude error should improve as error decreases due to the increased sensitivity. This will affect the Vertical Display implementation equipment.

(3) Increase Lateral Error Sensitivity - Increase the sensitivity of the path's lateral displacement to lateral errors, i.e., the path should be displaced much farther toward the horizon line for such initial conditions as 33.3 miles left than for 12.5 miles left. Pilots should be able to associate a displayed extent (or angle) of displacement with a given lateral error. Accuracy in estimating lateral error should improve as error decreases. This will affect the Vertical Display implementation equipment.

(4) Investigate a Vertical Position Planning Display - The Vertical Display necessarily becomes degraded in precision of information as the altitude error becomes very large. Whereas it is feasible to display specific path widths for specific altitude errors when there is a relatively small lateral error (line-of-sight distances), the display problem becomes more difficult as lateral error increases. Consider the initial condition of a 33 mile lateral error. The display of altitude changes in combination with this lateral error is necessarily much less precise than with no lateral error. In the present simulation, pilots had a horizontal presentation for planning purposes when there was a large lateral error, but no corresponding vertical presentation. It was difficult to detect small changes in altitude in combination with a large lateral error, the pilot relying somewhat on his knowledge of his own attitude inputs. End condition data for the Second Evaluation indicated median altitude error was over twice that of median lateral error, possibly due to the less precise information in the vertical plane. It is recommended that a vertical position planning presentation analogous to the horizontal presentation be investigated. This would present the orbital situation, similar to Figure 2, as part of the long range planning information on the Horizontal Display.

(5) Improve "Fly-Through" Presentation of Path - Eliminate present discontinuity in path altitude error presentation when vehicle is in close proximity to the path. Present display implementation results in a sudden switching of path position indicating a vehicle position above or below path commensurate with small altitude errors. This sudden switching has caused pilots to overcompensate for what appears to be a significant altitude error with resultant poor altitude control when on path. A smooth transition of path presentation is required to provide a more positive index of small altitude changes. This will affect the Vertical Display implementation equipment.

(6) Standardize Path Tip Displacement Distance for Heading and Elevation Errors - The gain in the path tip should be adjusted so that a given displacement from center constitutes the same angle (error) for both heading and elevation. Hence, pilots may learn that a specific tip displacement equals a specific angle regardless of the spatial plane he is attending to.

(7) Standardize Scale Factors on Common Drives to Path Tip and Background - The scale factors should be the same for drives to the Nominal Path tip and background elements. Background cues (horizon, ground plane, star field) provide secondary cues to established elevation and heading angles. It is axiomatic that these cues must verify the pilot's interpretation of an angle and, therefore, the scale factors to drives to the tip and background must be uniform.

(8) Quicken Feedback of Flight Parametric Information - In order that the pilot may anticipate the consequences of improper attitude management, it is recommended that a quickening of displays be investigated. The information fed back would be the parametric values (flight path angular and position errors) which would exist at some specified future time (e.g., 10 seconds or as required) if the vehicle continues on its present trajectory. In the Second Evaluation approaching the nominal path at a steep angle often resulted in passing through it and continuing on for many thousands of feet before the error could be corrected. Knowledge that "X" seconds from then the vehicle will pass through the nominal path should prompt the pilot to immediately correct his attitude and approach assymptotically rather than oscillating about the path. Predictor information would also compensate for some of the inherent lag between attitude command inputs and a visible change in movement of the flight path.

(9) Provide a More Positive Engine Cutoff Cue - The pulsing of the velocity marker provided good anticipatory indication of an approaching thrust requirement (initiation or cutoff). The disappearance of the markers, followed by their reappearance with rapid movement is a satisfactory cue for thrust initiation. The slowing, stopping and disappearance of the markers is not a satisfactory cue for thrust cutoff because it requires continuous monitoring and forces reliance on detecting the absence of a cue for initiation of a very critical discrete act. It is recommended that a more positive cue--possibly an auditory cue, separate display element or pulsation plus deletion of markers similar to the thrust initiation command--be activated at the exact moment that the engines should be cutoff. The velocity markers were not easily detected when the pathway was to the extreme left. It is recommended that there be markers on both the right and left side of the path for ease of detection under extreme lateral error conditions.

HORIZONTAL DISPLAY

(1) Improve Sensitivity to Lateral Error - Since the Horizontal Display elements are coordinated with the Vertical Display elements, sensitivity of the moving vehicle position symbol will also increase logarithmically as the nominal path is achieved. To facilitate detection of movement, it is recommended that the symbol be displaced much farther toward the periphery of the display. It would then be possible to tell that the vehicle was closing on the nominal path even at relatively gradual closure rates. The symbol should move continuously toward the nominal path (rather than switching back outward at critical periods as in the three-scale technique).

(2) Provide a More Realistic Task Loading - The use of the Status-Trend display, a first level of vehicle subsystem status monitoring, has proved to be too simple a task for pilot task loading. It is recommended that a more demanding procedure be incorporated in the next evaluation involving recognition of malfunctions in the vehicle systems that control the vertical display presentation (Guidance, Navigation and Control). Programmed deviations in the natural format of the vertical display would signal the malfunctions. Pilot query of the vehicle systems via presentations on the Horizontal Display, detection and correction of the malfunction by suitable control action, would provide a realistic task loading and also permit investigation of advanced vehicle subsystem monitoring concepts. In addition, ability to cope with potential malfunctions in the Space Analog will build confidence in this type of display.

4.0 COMPARISON OF THE FIRST AND SECOND EVALUATIONS

The objectives of the First and Second Evaluations differed considerably, hence any general comparison between median injection point performance must be made with recognition that differences in the display technique have been combined with other specific problems of interest in the particular evaluation. For example, the grand median performance for the First Evaluation was a composite of median performance under six conditions, three with analog information only and three with both analog and digital information. Also, investigated were different display gain settings. The grand median performance in the Second Evaluation was a composite of median performance under three scale and one scale conditions, with on-path and off-path initial conditions also analyzed within each group.

A comparison between the First and Second Evaluation was conducted by determining the grand medians for each parameter for the respective evaluations and by conducting a Mann-Whitney "U" Test, similar to that described previously, to determine the significance of the reported parameter medians. Table 14 presents the results of this comparison.

The major differences between the First and Second Evaluations may be summarized in terms of what they investigated. The First Evaluation was concerned primarily with determining the applicability of the analog display concepts to the cisplanetary injection maneuver, with the pilots following a command attitude profile in a manner similar to that currently employed or planned for the Gemini and Apollo missions. The First Evaluation demonstrated that a command attitude profile could be successfully flown with relatively small error in the relevant parameters. The First Evaluation provided information on "what am I doing" and "what should I be doing," but lacked information on "how am I doing." The Second Evaluation attempted to correct this deficiency, by permitting the pilot more control over the selection of appropriate elevation and heading angles and by allowing him to see his nominal path error. However, the Second Evaluation presented a task which required greater pilot participation and management, especially under the off-path initial conditions. The Second Evaluation demonstrated that it was feasible for pilots to perform a cisplanetary injection maneuver with feedback of nominal flight path error as the major information input.

The experimental design of the Second Evaluation incorporated the recommendations and conclusions of the First Evaluation as follows:

(1) The recommendation that the vertical display presentation be changed during the thrust period so that the pilot is able to receive information on "How am I doing" and can control the vehicle's position relative to the nominal path. This change, in effect, integrates the man into the loop as a command element rather than as a nuller of errors.

MEASURE	FIRST EVALUATION	SECOND EVALUATION	LEVEL*	TREND
ELEVATION ERROR	0.0025 deg	0.305 deg	.001	First
HEADING ERROR	0.003 deg	0.032 deg	.003	First
VELOCITY ERROR	5.0 fps	11.7 fps	.179	First
LATERAL ERROR	0.0 ft	2,488 ft	N/A	First
LONGITUDINAL ERROR	6,441 ft	2,799 ft	.006	Second
ALTITUDE ERROR	121 ft	6,560 ft	.001	First
PITCH ENERGY EXPENDITURE	29.0 %	16.12 %	.001	Second
YAW ENERGY EXPENDITURE	24.3 %	11.75 %	.001	Second
ROLL ENERGY EXPENDITURE	4.6 %	9.62 %	.014	First

* Level of significance (Mann-Whitney "U" Test)

TABLE 14

COMPARISON OF THE GRAND MEDIAN SCORES

FOR THE FIRST AND SECOND EVALUATIONS

(2) The recommendation to include scale changes in both vertical and horizontal positional error to investigate the display of rates of closure between the vehicle and the nominal path.

(3) The recommendation to use analog information alone; digital backup information was unnecessary.

(4) The conclusion that rate attitude control rather than acceleration attitude control should be used.

(5) The conclusion that in the First Evaluation a realistic level of performance with a standard TV roster analog display was determined against which more advanced display techniques could be compared.

It was predicted that the incorporation of Recommendations #2 through #5 would act in the direction of improving performance in the Second Evaluation. Recommendation #1, which resulted in changing the meaning of the flight path and view of the display in the Second Evaluation, would not necessarily result in better initial performance, but with improved display techniques, could eventually result in better performance.

4.1 Performance Differences in the First and Second Evaluations

It can be seen in Table 14 that four of the six parameters favoring the First Evaluation were highly significant (.02 or better). These parameters were elevation error, heading error, altitude error, and roll energy expenditure. The level of significance for a fifth parameter, lateral error, could not be assessed because the First Evaluation reported this error as essentially zero. The sixth parameter, velocity error, was significant at a very low level (.18). An explanation for the superior performance on these parameters in the First Evaluation was the extremely fine display sensitivity to small errors which was achieved through the use of a command attitude presentation.

Table 14 indicates that three parameters favored the Second Evaluation and were highly significant (.06 or better). These parameters were longitudinal error, pitch and yaw energy expenditure. An explanation for the lower control energy expenditures in pitch and yaw was that in the First Evaluation pilots tended to overcontrol by correcting for insignificant errors, whereas in the Second Evaluation pilots were less aware of very small deviations from an idealized vehicle flight path, and hence, corrected much less often. Roll commands were rarely introduced in the First Evaluation, the pilots relying much more often on pitch and yaw commands.

The parameters reported in Table 14 are grand medians and the Mann-Whitney tests were conducted only between these grand medians, which included both on-path and off-path initial conditions. Since the Second Evaluation reported much poorer performance for the off-path condition than did the First Evaluation (the off-path or on-path condition being much less consequence in an error nulling task), it was decided to compare best performance in the Second Evaluation with performance for the First Evaluation. This data is presented in Table 15. Note that the differences in values are much less between the two evaluations.

4.2 Space Systems Applications

Table 15 presents a comparison of injection point data with representative space system performance requirements. System requirements listed below as allowable errors for interplanetary missions are based on the EMPIRE Program and Apollo.

Parameters		Median Errors* First Evaluation	Median Errors** Second Evaluation	Allowable Error for Interplanetary Missions
Flight Path Elevation	(DEG)	0.0025	0.192	0.1
Flight Path Heading	(DEG)	0.003	0.009	0.1
Velocity	(FPS)	5.0	7.3	4 to 10
Lateral Position (out-of-plane)	(FT)	Essentially Zero	1,027	50 to 11,000
Longitudinal Position (in-plane)	(FT)	6,441	1,181	50 to 11,000
Altitude	(FT)	121	4,368	3,000
Pitch Energy Expend.	(%)	29.0	13.68	N/A
Yaw Energy Expend.	(%)	24.3	8.28	N/A
Roll Energy Expend.	(%)	4.6	5.48	N/A

* Grand Median
** On-path, 1-scale

TABLE 15

COMPARISON OF FIRST AND SECOND EVALUATION MEDIAN SCORES WITH SPACE MISSION ALLOWABLE ERRORS

Of the first six parameters listed above on which allowable error data is available, the First Evaluation median performance is either more accurate or within the range of accuracies required for a successful injection on all of the parameters. Median data for the Second Evaluation meets allowable error requirements on all but two of the parameters, flight path elevation error and altitude error. This observation confirms the recommendation that additional display sensitivity is needed to improve pilot performance on these two parameters.

The interplanetary requirements are tentative and based on the best available current data. As such, it is subject to revision and more exact definition as interplanetary planning advances.

4.3 Conclusion

The First Evaluation established the level of performance of a standard TV presentation space analog with pilot nulling of computer determined vehicle attitude errors.

The Second Evaluation determined an initial level of pilot performance when the Space Analog format permitted pilot management of the vehicle flight path with respect to a required (nominal) path. The use of a constant display gain resulted in relatively acceptable flight performance under ideal control conditions but with inherent display deficiencies under poor control or high error conditions. The Second Evaluation has also indicated the direction for further improvement of the Space Analog: (1) the incorporation of non-linear gain in the presentation of vehicle flight path deviations from the Nominal, and (2) the investigation and application of quickened and predictive information to improve display response to pilot control inputs.

5.0 PROGRAM RECOMMENDATIONS

The results of the first two program simulations have shown the Space Analog Display to be a feasible means for control of space vehicles during orbital maneuvers. The Second Evaluation has further indicated that operation in the Space Vehicle Path Mode permits a higher level of decision making and participation on the part of the pilot than when simply nulling computer presented errors as the case in the Space Vehicle Command Attitude Mode of the First Evaluation. The Second Evaluation has also defined the need for further research in specific areas which should result in a higher level of pilot performance. This research can be accomplished with equipment and facilities presently available to the program with required but limited modification in certain specific areas. It is therefore recommended that a Third Evaluation be conducted in the LTV Manned Aerospace Flight Simulator (MAFS) to correct the deficiencies in the Space Analog that have been identified.

5.1 OBJECTIVES

The objectives of the Third Evaluation are:

(1) Improve the natural presentation of space vehicle flight path angular and positional errors with respect to a required (Nominal) path by investigating techniques for providing a logarithmic or non-linear increase in display sensitivity as error is decreased and a decrease in sensitivity as error is increased.

(2) Improve displayed vehicle flight path response to attitude control when thrusting by investigating techniques for incorporating quickened and/or predictor forms of information in the Space Analog to compensate for the inherent lag between pilot attitude control inputs and the visable change in vehicle flight path.

(3) Revise the Vertical Display System Demonstrator equipment to correct deficiencies in display element presentation.

(4) Incorporate an Earth capture flight profile, in lieu of the cisplanetary injection profile previously used, to extend the investigation of the operational capabilities of the Space Analog to another critical phase of the space mission.

(5) Investigate pilot ability to recognize malfunctions of the Space Analog by observation of display element performance (programmed random deviations from the natural environmental format) in the course of normal space flight operation; and to identify and correct such system malfunctions through the interpretation of advanced integrated forms of vehicle subsystem status information appearing on the Horizontal Display, and applicable panel controls. This will serve as a more realistic form of operational pilot task loading than the first level of information Status-Trend display used during the first two simulator evaluations.

(6) Define the envelope of flight operation for the Vertical Display portion of the Space Analog, i.e., what are the limits, if any, in off Nominal Path vehicle conditions, which retain a natural environmental display format and do not require supplementary planning information for normal flight operation? (Is it line-of-sight distance to the Nominal Path and/or other factors?)

5.2 TECHNICAL APPROACH

The Third Evaluation will consist of:

(1) Review current concepts and applications of logarithmic or non-linear gain, quickened, and predictor techniques for information display. Select specific techniques for application to the Space Analog and simulator evaluation.

(2) Review current concepts for space vehicle Earth capture maneuvers and select one that is most representative of future manned space flight.

(3) Review the circuitry of the Vertical Display Pathway Display System Demonstrator and define specific hardware changes needed to correct presently defined deficiencies in display element presentation. Coordinate this with the equipment manufacturer. Implement the required changes by revising existing or procuring new circuit boards for the System Display Generator.

(4) Setup the LTV MAFS and its supporting computer complex incorporating the Earth capture flight profile and revised Vertical Display Pathway Display System Demonstrator. Prepare a test program incorporating the test objectives defined.

(5) Conduct a three week test program utilizing, if possible, the same pilot subjects as in the preceding two simulator evaluations.

(6) Reduce and evaluate test data and compare to the results of the previous Evaluations and to current requirements for manned Mars, Venus and Apollo space programs.

(7) Prepare a formal report containing descriptions of the simulation setup, test procedures, data acquired, evaluation procedures, results, conclusions, and recommendations for further research. In addition prepare a documentary film illustrating the display presentations evaluated.

5.3 ANTICIPATED RESULTS

It is expected that the Third Evaluation will produce the following results:

(1) The deficiencies in the Space Vehicle Path Mode defined in the Second Evaluation will be corrected and the resultant pilot flight performance will compare closely with that of the Space Vehicle Command Mode of the First Evaluation. Further, it will be shown that the Space Analog concept of information presentation meets the requirements of current and future

space systems in a manner that permits maximum manned participation and decision making during the most critical phases of space flight.

(2) Demonstration of a pilot's ability to recognize and correct possible malfunctions in the space analog will increase confidence and acceptance of this form of information presentation.

(3) The application of advanced integrated information presentation to vehicle subsystem malfunction detection and correction, used in conjunction with Space Analog malfunction recognition and as pilot task loading, will demonstrate the advantages of these concepts in this area.

6.0 REFERENCES

1. Jarrell, L., Space Mission Definition, LTV Astronautics Division Report No. 00.307, NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems, April 1964.

2. Koppa, R. J., A Survey of Current Display and Control Concepts, LTV Astronautics Division Report No. 00.308, NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems, March 1964.

3. Brown, E. S., et. al., Mission-Function-Task Analysis, LTV Astronautics Division Report No. 00.316, NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems, March 1964.

4. Burke, J. E., Summary Report - Requirements Analysis Phase, LTV Astronautics Division Report No. 00.385, NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems, April 1964.

5. LTV Engineering Department Specification No. 304-447C, Procurement Specification for Pathway Display System Demonstrator, dated 3 August 1965.

6. Obermayer, R. W., and Muckler, F. A., Performance Measurement in Flight Simulator Studies, AIAA, Simulation for Aerospace Flight Conference - A Volume of Technical Papers, August 26-28, 1963. pp 58-65.

7. Koppa, R. J., Simulation Program Plan - First Evaluation, LTV Astronautics Division Report No. 00.454, NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems, dated August 1964.

8. Koppa, R. J., Pilot Handbook - First Simulator Evaluation (Cisplanetary Injection), LTV Astronautics Division Report No. 00.743, NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems, dated January 1966.

9. Siegel, S., Nonparametric Statistics for the Behavioral Sciences, New York: McGraw-Hill, 1956, pp 116-127.

10. Huchingson, R. D., Pilot Handbook - Second Simulation Evaluation, LTV Astronautics Division Report No. 00.814, NASA Contract NASw-611, Evaluation of Advanced Integrated Display and Control Systems, dated June 1966.

APPENDIX I-A

FIRST EVALUATION - SIMULATION EQUATIONS

CONTENTS

CONTENTS (Cont'd)

FIGURES

TABLES

1.0 DEFINITION OF SYMBOLS

Symbol	Definition
e	Eccentricity of nominal trans-Mars orbit.
GM	Gravitational constant.
h	Vehicle altitude relative to reference sphere (Earth).
Δh	Altitude error relative to nominal trajectory.
h_{DIS}	Vertical display altitude drive signal.
Δh_{DIS}	Vertical display altitude error drive signal.
$\dot{h}_{REF}$	Reference altitude rate in attitude command computation.
$\Delta \dot{h}_{REF}$	Reference altitude rate resulting from Δh.
I_{SP}	Specific impulse, main engine.
$K_{1,2,3}$	Logic terms for computation of vertical display angular drive gains.
$K_{C,N}$	Logic terms associated with display mode selection.
K_E	Logic term associated with main engine operation.
K_G	Represents K_G, 1,2,3,4, or 5 in computation of display angle gains.
$K_{G1,2,3,4,5}$	Vertical display angular drive gains.
$K_{h_{DIS}}$	Vertical display altitude error sense signal.
$K_{\dot{h}}, K_{\dot{\gamma}_0}, K_{\Delta h}, K_{\gamma_P}$	Gains in attitude command equations.
K_I	Logic term associated with first initiation of thrust (time to even computation).

Symbol	Definition
$K_{p_{1,2,3,4}}$	Inertia coupling constants in roll.
$K_{q_{1,2,3,4}}$	Inertia coupling constants in pitch.
$K_{r_{1,2,3,4}}$	Inertia coupling constants in yaw.
$K_{R_{\dot{Z}}}$	Logic term associated with speed marker velocity error computation.
$K_{\Delta t}$	Logic term associated with total thrusting time.
$K_{\otimes}$	Logic term associated with orbital longitude relative to nominal insertion (thrust termination).
$K_{\theta_A}, K_{\psi_A}, K_{\phi_A}$	Pitch, yaw, and roll gains for automatic attitude control.
$l_{1,2,3}\ m_{1,2,3}\ n_{1,2,3}$	Direction cosines relating $X_BY_BZ_B$ body axes to $Y_PY_PZ_P$ inertial axes.
$\dot{l}_{1,2,3}\ \dot{m}_{1,2,3}\ \dot{n}_{1,2,3}$	Rates of change of $l_{1,2,3}$, $m_{1,2,3}$, $n_{1,2,3}$ direction cosines.
$l_{o_{1,2,3}}\ m_{o_{1,2,3}}\ n_{o_{1,2,3}}$	Direction cosines relating $X_BY_BZ_B$ body axes to $X_OY_OZ_O$ local horizontal-vertical axes.
p, q, r	Inertial angular rates about $X_BY_BZ_B$ body axes - roll, pitch, yaw.
$\dot{p}, \dot{q}, \dot{r}$	Inertial angular accelerations about $X_BY_BZ_B$ body axes.
$p_{c_s}, q_{c_s}, r_{c_s}$	Stick commanded angular rates.
q_{c_T}, r_{c_T}	Trim knob commanded angular rates.
p_e, q_e, r_e	Attitude control system angular rate errors.
$\Delta p_s, \Delta q_s, \Delta r_s$	Attitude control system thruster fuel measures, ideal angular velocities expended about each body axis.
$\Delta \dot{p}_s, \Delta \dot{q}_s, \Delta \dot{r}_s$	Angular acceleration contributions of attitude control system thrusters.

Symbol	Definition
$\Delta\dot{q}_E, \Delta\dot{r}_E$	Angular acceleration contributions resulting from main engine misalignment moments.
$\Delta\dot{q}_{E_0}, \Delta\dot{r}_{E_0}$	Initial values of $\Delta\dot{q}_E$ and $\Delta\dot{r}_E$.
$d\dot{q}_E/d\frac{T}{m}, d\dot{r}_E/d\frac{T}{m}$	Variations of $\Delta\dot{q}_E$ and $\Delta\dot{r}_E$ with thrust-to-mass ratio.
r_E	Radius of reference sphere (Earth).
r_{NOM}	Radius of nominal trajectory from center of reference sphere (Earth).
r_P	Radius of nominal trajectory prior to insertion (thrust termination) and perigee radius of nominal trans-Mars trajectory.
r_V	Local radius of flight path (vehicle distance) from center of reference sphere (Earth).
r_{V_I}	Flight path radius at thrust initiation.
R_Z	Longitudinal range on surface of reference sphere (Earth) from nominal insertion (thrust termination).
R_{Z_I}	Longitudinal range preset for thrust initiation.
$R_{Z_{1,2,3,\cdots 10,11}}$	Longitudinal range terms for scheduling speed marker on-off logic.
$R_{Z_{12}}$	Longitudinal range term for changing speed marker velocity error computation at thrust initiation.
s	Laplace operator.
t	Elapsed time from run initiation.
Δt_A	Lead time in velocity error computation.
Δt_B	Total thrusting time.
t_{TG}	Time to event.
$\Delta t_{1,2,3,\cdots 11,12}$	Time terms for computation of $R_{Z,1,2,3\ldots 11,12}$.
T/m	Thrust-to-mass ratio.
T/m_0	Initial thrust-to-mass ratio.

Symbol	Definition
V	Resultant inertial velocity.
V_{CORR}	Velocity change required.
V_E	Vertical display velocity error signal.
V_H	Projection of inertial velocity in local horizontal.
V_{NOM}	Nominal insertion (thrust termination) velocity.
V_P	Perigee velocity of nominal trans-Mars trajectory.
V_{PATH}	Vertical display pathway velocity signal.
V_{REQ}	Required velocity, digital readouts.
ΔV	Main engine fuel measure, ideal velocity expended.
$V_{\parallel DIS}$	Vertical display ground plane velocity signal parallel to reference heading.
$V_{\perp DIS}$	Vertical display ground plane velocity signal normal to reference heading.
$\Delta\ddot{X}_B$	Thrust resultant acceleration along X_B body axis.
$\dot{X}_O, \dot{Y}_O, \dot{Z}_O$	Inertial velocity components in $X_O Y_O Z_O$ local horizontal-vertical reference system.
X_P, Y_P, Z_P	Inertial position coordinates in $X_P Y_P Z_P$ inertial reference system.
$\dot{X}_P, \dot{Y}_P, \dot{Z}_P$	Inertial velocity components in $X_P Y_P Z_P$ inertial reference system.
$\ddot{X}_P, \ddot{Y}_P, \ddot{Z}_P$	Inertial acceleration components in $X_P Y_P Z_P$ inertial reference system.
$\Delta\ddot{X}_P, \Delta\ddot{Y}_P, \Delta\ddot{Z}_P$	Thrust resultant accelerations in $X_P Y_P Z_P$ inertial reference system.
X_R	Projection of local flight path radius (r_V) in X_P-Z_P plane.
$\dot{X}_R$	**Inertial velocity in X_P-Z_P plane along radius vector projection.**
$Y_{C_{CRT}}, Z_{C_{CRT}}$	Horizontal situation display CRT coordinates associated with command flight path heading line (end of line away from vehicle position depicting direction of command heading).

Symbol	Definition
Y_{HCRT}, Z_{HCRT}	Horizontal situation display CRT coordinates associated with present flight path heading line (end of line away from vehicle position depicting direction of present heading).
$\dot{Y}_{0REF}$	Reference lateral velocity in attitude command computation.
Y_{VCRT}, Z_{VCRT}	Horizontal situation display CRT coordinates associated with vehicle position and present and command flight path heading lines (end of both lines which corresponds to present vehicle position).
ΔY_{DIS}	Vertical display pathway lateral offset signal.
Z_{ICRT}	Horizontal situation display CRT position associated with thrust initiation command line.
$Ⓨ_{RP}$	Orbital longitude, central angle in X_P-Z_P plane relative to X_P axis (nominal insertion).
$Ⓩ_{RO}$	Orbital latitude, central angle displacement from X_P-Z_P plane (nominal orbital plane).
α	Represents $\Psi_3, \Theta_3, \Phi_3, \Psi_E$, or $K_C\Theta_E$ in computation of display angle gains.
γ	Actual flight path elevation from local horizontal plane.
γ_{NOM}	Nominal trajectory flight path elevation from local horizontal plane.
$\delta_{sp}, \delta_{sq}, \delta_{sr}$	Attitude control, side stick deflections in roll, pitch, and yaw.
δ_{Tq}, δ_{Tr}	Attitude control, trim knob deflections in pitch, and yaw.
$\varepsilon_{\theta ABS}, \varepsilon_{\phi ABS}, \varepsilon_{\psi ABS}$	Integrated absolute error in pitch, roll and yaw.
ϵ_V	Instantaneous velocity error.
ϵ_γ	Instantaneous flight path elevation error.
$\epsilon_\theta, \epsilon_\psi$	Instantaneous errors in pitch and yaw.

Symbol	Definition
θ_3, ϕ_3, ψ_3	Pitch, roll, and yaw Euler angles for vehicle orientation relative to local horizontal-vertical reference system.
θ_c, ψ_c	Pitch, and yaw commanded attitudes.
$\theta_{CORR}, \phi_{CORR}, \psi_{CORR}$	Pitch, roll, and yaw attitude change requirements - digital readouts.
$\theta_{DIS}, \phi_{DIS}, \psi_{DIS}$	Vertical display, angular drive signals in pitch, roll, and yaw.
θ_E, ψ_E	Pitch and heading (yaw) errors.
$\theta_{E_{DIS}}, \psi_{E_{DIS}}$	Vertical display, pathway angular drive signals in pitch error and heading error.
θ_{REF}	Reference pitch angle in attitude command computation.
ψ_H	Actual flight path heading in local horizontal plane relative to reference heading (nominal orbital plane).

2.0 EQUATIONS

The implementation of the First Evaluation Simulator program included the computation of vehicle motion in six degrees-of-freedom, vehicle configuration variations, attitude control system operation, display drive signals, moving base drive signals, and data recording parameters.

2.1 TRANSLATIONAL MOTION

The translation, position and velocity, of the vehicle were computed in a geocentric, inertially oriented axis system - X_P, Y_P, Z_P. The X_P-Z_P plane was the nominal orbital plane with the X_P axis coinciding with the local radius vector at the nominal insertion, thrust termination point.

2.1.1 Equations of Motion

The equations of translational motion in the inertial reference system were:

$$\ddot{X}_P = \Delta\ddot{X}_P - \frac{GM}{r_v^3} X_P \tag{1}$$

$$\ddot{Y}_P = \Delta\ddot{Y}_P - \frac{GM}{r_v^3} Y_P \tag{2}$$

$$\ddot{Z}_P = \Delta\ddot{Z}_P - \frac{GM}{r_v^3} Z_P \tag{3}$$

The thrust resultant accelerations in equations 1, 2, and 3, were determined from:

$$\begin{bmatrix} \Delta\ddot{X}_P \\ \Delta\ddot{Y}_P \\ \Delta\ddot{Z}_P \end{bmatrix} = \begin{bmatrix} l_1 & m_1 & n_1 \\ l_2 & m_2 & n_2 \\ l_3 & m_3 & n_3 \end{bmatrix} \begin{bmatrix} \Delta\ddot{X}_B \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

Thrust resultant accelerations were produced in the vehicle along only the longitudinal, X_B, axis - the acceleration along Y_B and Z_B always being zero:

$$\Delta \ddot{X}_B = K_E \left(T/m \right) \tag{5}$$

2.1.2 <u>Geometric Definitions</u>

The geometric relationship of the various axis systems and terminologies used in the simulation were as shown in Figure I-A-1. The magnitude of the radius vector for the present position of the vehicle was computed from

$$r_v = + \left(X_R^2 + Y_P^2 \right)^{1/2} \tag{6}$$

where the projection of the radius vector into the X_P - Z_P plane was

$$X_R = + \left(X_P^2 + Z_P^2 \right)^{1/2}. \tag{7}$$

The altitude of the vehicle above the surface of the reference sphere - Earth assumed to be spherical - was determined from the radius vector:

$$h = r_v - r_E \quad . \tag{8}$$

The polar angles of vehicle position relative to the nominal orbital plane and insertion point were orbital longitude

$$\sin \Theta_{RP} = Z_P / X_R \tag{9}$$

$$\cos \Theta_{RP} = X_P / X_R \tag{10}$$

and orbital latitude

$$\sin \Phi_{RD} = Y_P / r_v \tag{11}$$

$$\cos \Phi_{RD} = X_R / r_v \quad . \tag{12}$$

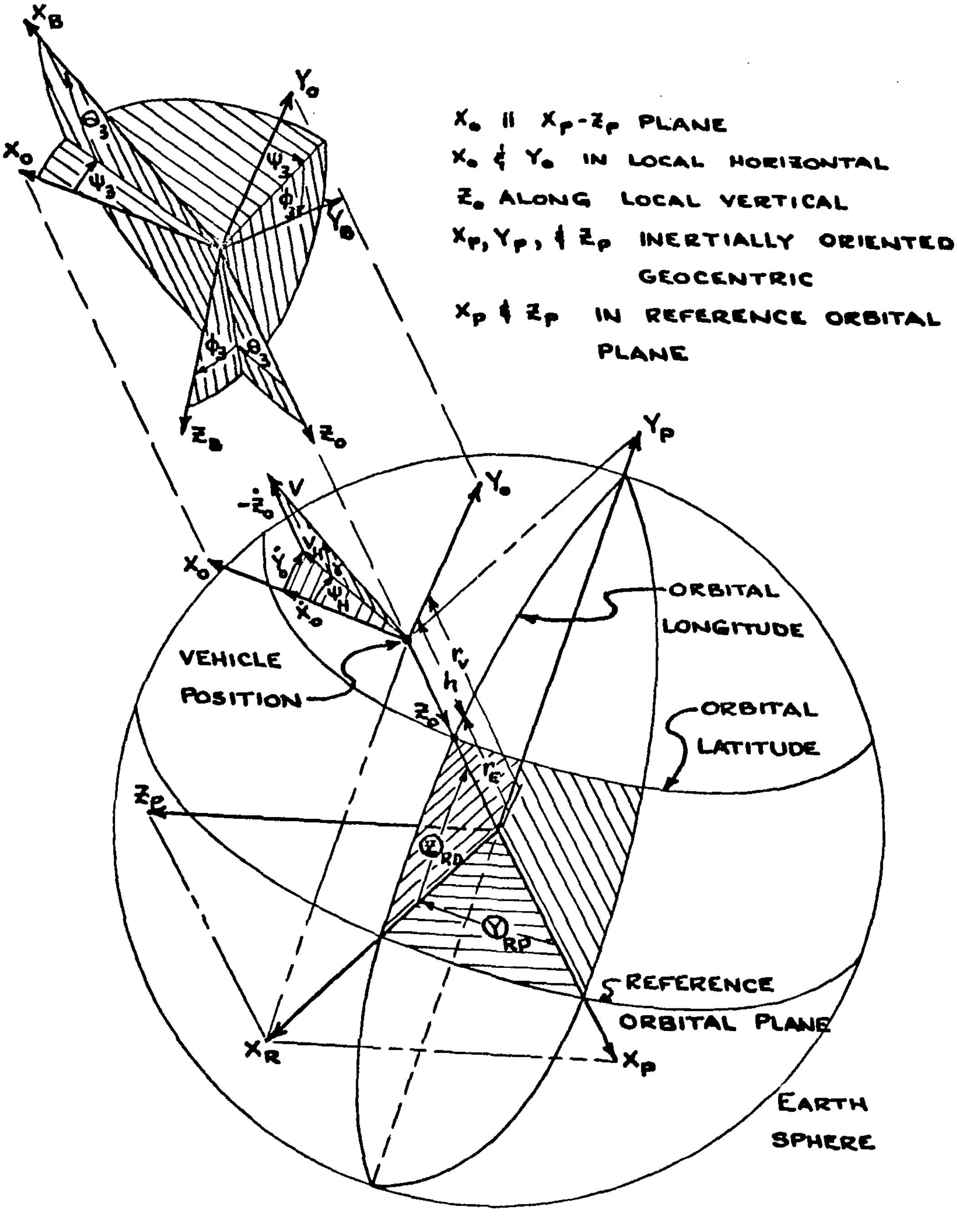


FIGURE I-A-1 SIMULATION GEOMETRY

The components of vehicle inertial velocity in the Earth referenced local horizontal and vertical of present vehicle position were computed from:

$$\dot{X}_o = -\dot{X}_P \sin \textcircled{Y}_{RP} + \dot{Z}_P \cos \textcircled{Y}_{RP} \qquad (13)$$

$$\dot{Y}_o = -\dot{X}_R \sin \textcircled{Z}_{RD} + \dot{Y}_P \cos \textcircled{Z}_{RD} \qquad (14)$$

$$\dot{Z}_o = -\dot{X}_R \cos \textcircled{Z}_{RD} - \dot{Y}_P \sin \textcircled{Z}_{RD} \qquad (15)$$

where the vehicle velocity in the nominal orbital plane, X_P - Z_P, along the projection of the radius vector was:

$$\dot{X}_R = \dot{X}_P \cos \textcircled{Y}_{RP} + \dot{Z}_P \sin \textcircled{Y}_{RP} \,. \qquad (16)$$

The resultant inertial velocity of the vehicle was:

$$V = +\left[V_H^2 + (\dot{Z}_o)^2 \right]^{1/2} \qquad (17)$$

with the local horizontal component being:

$$V_H = +\left[(\dot{X}_o)^2 + (\dot{Y}_o)^2 \right]^{1/2} . \qquad (18)$$

The orientation of the flight path relative to the reference nominal orbital (X_P - Z_P) plane and local horizontal was defined by the flight path heading:

$$\sin \Psi_H = \dot{Y}_o / V_H \qquad (19)$$

$$\cos \Psi_H = \dot{X}_o / V_H \qquad (20)$$

and flight path elevation angle

$$\sin \gamma = -\dot{Z}_o / V \qquad (21)$$

$$\cos \gamma = V_H / V \,. \qquad (22)$$

2.2 ROTATIONAL MOTION

The rotational motion of the vehicle was defined in terms of body axis inertial angular accelerations and rates, the direction cosines relating the orientation of the vehicle body axes to both the inertial reference and the local horizontal and vertical axes, and the Euler angles which defined vehicle attitude relative to the local horizontal and vertical axes.

2.2.1 Equations of Motion

The equations of rotational motion for computing the body axis inertial angular acceleration were:

$$\dot{p} = \Delta\dot{p}_s + K_{p_1} qr + K_{p_2}(q^2 - r^2) + K_{p_3}(\dot{r} + pq) + K_{p_4}(\dot{q} - pr) \quad (23)$$

$$\dot{q} = \Delta\dot{q}_s + \Delta\dot{q}_E + K_{q_1} pr + K_{q_2}(r^2 - p^2) + K_{q_3}(\dot{p} + qr) + K_{q_4}(\dot{r} - pq) \quad (24)$$

$$\dot{r} = \Delta\dot{r}_s + \Delta\dot{r}_E + K_{r_1} pq + K_{r_2}(p^2 - q^2) + K_{r_3}(\dot{q} + pr) + K_{r_4}(\dot{p} - qr) . \quad (25)$$

The constants in equations 23, 24, and 25 - K_P, K_{P_2}, K_{q_3}, K_{r_4}, etc. reflect the assumption of constant moments of inertia for the simulated vehicle.

2.2.2 Direction Cosines

The direction consines relating body axis orientation relative to the reference, inertial axes - X_P, Y_P, Z_P - were computed from the body axis angular rates:

$$\begin{bmatrix} \dot{l}_1 & \dot{m}_1 & \dot{n}_1 \\ \dot{l}_2 & \dot{m}_2 & \dot{n}_2 \\ \dot{l}_3 & \dot{m}_3 & \dot{n}_3 \end{bmatrix} = \begin{bmatrix} l_1 & m_1 & n_1 \\ l_2 & m_2 & n_2 \\ l_3 & m_3 & n_3 \end{bmatrix} \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} . \quad (26)$$

The direction cosines relating body axis orientation relative to the local horizontal and vertical axes - X_O, Y_O, Z_O were:

$$\begin{bmatrix} -l_{o_3} & -m_{o_3} & -n_{o_3} \\ l_{o_2} & m_{o_2} & n_{o_2} \\ l_{o_1} & m_{o_1} & n_{o_1} \end{bmatrix} = \begin{bmatrix} \cos\Theta_{RD} & \sin\Theta_{RD} & 0 \\ -\sin\Theta_{RD} & \cos\Theta_{RD} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\Theta_{RP} & 0 & \sin\Theta_{RP} \\ 0 & 1 & 0 \\ -\sin\Theta_{RP} & 0 & \cos\Theta_{RP} \end{bmatrix} \begin{bmatrix} l_1 & m_1 & n_1 \\ l_2 & m_2 & n_2 \\ l_3 & m_3 & n_3 \end{bmatrix} . \tag{27}$$

2.2.3 Attitude Angles

The vehicle attitude - body axis orientation relative to the reference, nominal orbital plane, heading and local horizontal plane - was defined for a yaw-pitch-roll Euler angle convention as shown in Figure I-A-1.

$$\sin\theta_3 = -l_{o_3} \tag{28}$$

$$\cos\theta_3 = +\left(1 - l_{o_3}^2\right)^{1/2} \tag{29}$$

$$\sin\psi_3 = l_{o_2}/\cos\theta_3 \tag{30}$$

$$\cos\psi_3 = l_{o_1}/\cos\theta_3 \tag{31}$$

$$\sin\phi_3 = m_{o_3}/\cos\theta_3 \tag{32}$$

$$\cos\phi_3 = n_{o_3}/\cos\theta_3 \quad . \tag{33}$$

2.3 VEHICLE CONFIGURATION VARIABLES

2.3.1 Mass

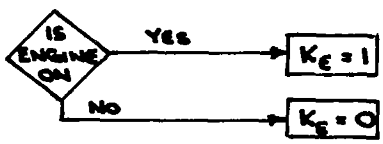
The simulated vehicle was assumed to vary mass only as a function of fuel consumption by the main, nuclear propulsion engine which was assumed to produce constant thrust. Since actual mass and thrust magnitudes were of no concern for this simulation, it was important then to compute only the variations in thrust-to-mass ratio. For a vehicle with a **constant** thrust engine and which varies mass only as a result of operation of that engine, variations of the thrust-to-mass ratio are a function of only the initial thrust-to-mass ratio, the specific impulse of the propellant, and the total operating time of the engine. This approach was used for the computation of thrust-to-mass ratio:

$$T/m = \frac{32.2\, I_{sp}\,(T/m_o)}{32.2\, I_{sp} - \Delta t_B\,(T/m_o)} \quad . \tag{34}$$

Engine burn, operating time was determined from:

$$\Delta t_B = \int_0^t K_E\, dt \tag{35}$$

where the logic term, K_E, was determined from:



2.3.2 Moments of Inertia and Center of Mass

The moments, and products, of inertia of the simulated vehicle were assumed to be constants, but the center of mass was assumed to vary in the Y_B and Z_B body axis directions. Assuming the attitude control jets to be arranged to produce pure rotational couples, the only effects of a variable center of mass are associated with the resultant misalignment of the main engine thrust vector producing rotational moments in pitch and yaw. A simplified routine was used in the simulation to compute the angular acceleration contributions resulting from the thrust vector not being aligned through the center of mass.

$$\Delta \dot{q}_E = K_E \left[\Delta \dot{q}_{E_o} + \frac{T}{m} \left(d\dot{q}_E / d\frac{T}{m} \right) \right] \tag{36}$$

$$\Delta \dot{r}_E = K_E \left[\Delta \dot{r}_{E_o} + \frac{T}{m} \left(d\dot{r}_E / d\frac{T}{m} \right) \right] \quad . \tag{37}$$

2.4 ATTITUDE CONTROL

Attitude control of the vehicle was performed by means of the 3-axis side stick controller in either a RATE command or ACCELERATION command, direct, mode. Trim knobs in pitch and yaw were available for providing supplementary rate command signals when operating in the RATE command mode, only. Except for the trim functions, none was available in the roll loop, all three control loops were identical and the single attitude mode switch in the cockpit changed mode in all three loops simultaneously. A schematic of the attitude control system as simulated is shown in Figure I-A-2. Automatic control of attitude was also provided for use as required. A simplified approach was used wherein the rotational equations of motion - 22, 23, and 24, and the attitude control system were bypassed with the body axis rates being computed as functions of roll displacement and pitch and yaw attitude errors:

$$p = \left[-K_{\phi_A} \phi_s \right]_{\lim \pm 10°/s} \tag{38}$$

$$q = \left[-K_{\theta_A} \theta_E \right]_{\lim \pm 10°/s} \tag{39}$$

$$r = \left[-K_{\psi_A} \psi_E \right]_{\lim \pm 10°/s} \tag{40}$$

2.5 DISPLAY DRIVE SIGNALS

2.5.1 Vertical Display Angular Drives

The angular drive signals to the vertical display were implemented such that the effects of varying the gain of the displayed angle could be evaluated. In addition to displaying the true values of the angles; i.e., using a constant unity gain between displayed and actual values; two approaches were available wherein the gain was varied.

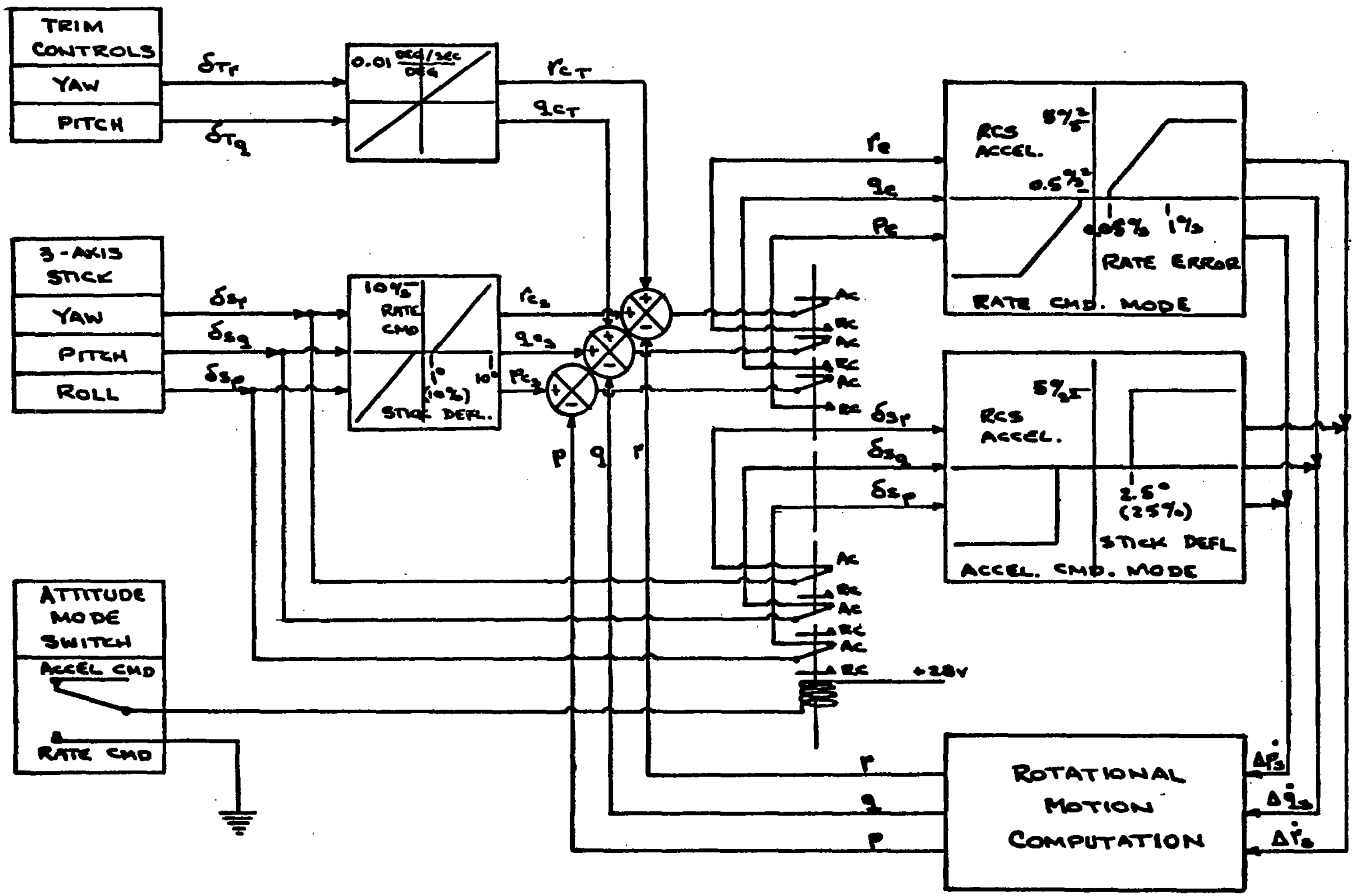


FIGURE I-A-2 ATTITUDE CONTROL SYSTEM SCHEMATIC

In one, a step change in gain was made when the absolute value of the angle was equal to one degree. When the actual angle was less than an absolute one degree, the displayed value was 5 times the magnitude of the actual value, a gain of 5 between displayed and actual. For actual values greater than an absolute one degree the displayed value was equal to the actual, a unity gain.

In the other approach to variable display gains, the gain was continuously varied between unity and 5 when the absolute value of the actual angle was in the range of 0.1 to 10 degrees such that the displayed value was a linear function of the actual. For actual values greater than an absolute 10 degrees and less than 0.1 degree the gain was constant at unity and 5, respectively.

Selection of the display gain method to be used was available only at the computer, and only one of the three methods being used for any given run. The angular drive signals for the vertical display are defined below.

2.5.1.1 Ground Plane, Horizon, and Starfield Orientation

The Orientation of the ground plane, horizon, and starfield were obtained from sine and cosine inputs of the displayed values of yaw, pitch, and roll:

$$\psi_{DIS} = K_{G_1} \psi_3 \tag{41}$$

$$\theta_{DIS} = K_{G_2} \theta_3 \tag{42}$$

$$\phi_{DIS} = K_{G_3} \phi_3 \ . \tag{43}$$

2.5.1.2 Pathway Orientation

The orientation of the pathway was defined by sine and cosine values of the displayed values of the heading and pitch error terms:

$$\psi_{E_{DIS}} = \left[K_{G_4} \psi_E \right]_{lim \pm 20°} \tag{44}$$

$$\Theta_{E_{DIS}} = \left[K_{G_5} K_c \Theta_E \right]_{lim \; {}^{+15°}_{-12°}} \; . \tag{45}$$

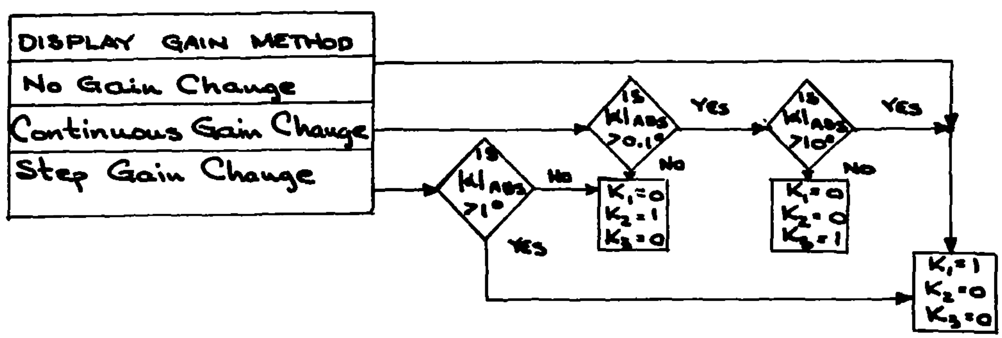
The display gains - K_{G_1}, K_{G_2}, etc. for each of the displayed angles were determined as follows:

Letting $\alpha = \psi_S, \Theta_S, \phi_S, \psi_E$, or $K_c \Theta_E$

and $K_G = K_{G_1}, K_{G_2}, K_{G_3}, K_{G_4}$, or K_{G_5}

then: $$K_G = K_1 + 5 K_2 + \left(\frac{2.375 |\alpha|_{ABS} + 1}{2.475 |\alpha|_{ABS}} \right) K_3 \tag{46}$$

where the logic terms K_1, K_2, and K_3 are determined from:



The heading and pitch error terms used in equations 44 and 45 were computed from:

$$\psi_E = \psi_3 - K_c \psi_c \tag{47}$$

$$\theta_E = \theta_3 - K_c \theta_c \ . \tag{48}$$

The heading and pitch command terms of equations 47 and 48 were determined from:

$$\psi_c = \left[K_{\dot{Y}_o} \left(\dot{Y}_{o_{REF}} - \dot{Y}_o \right) \right]_{\lim \pm 45^\circ} \tag{49}$$

$$\theta_c = \left[\theta_{REF} + K_{\dot{h}} \left(\dot{h}_{REF} + \dot{z}_o \right) \right]_{\lim \pm 80^\circ} \tag{50}$$

$$\dot{Y}_{o_{REF}} = K_{\Delta t} \left(\frac{2 Y_p}{\Delta t_B - 400} \right) - (1 - K_{\Delta t}) K_{Y_p} Y_p \tag{51}$$

$$\dot{h}_{REF} = \Delta \dot{h}_{REF} + V \sin \gamma_{NOM} \tag{52}$$

$$\Delta \dot{h}_{REF} = K_{\Delta t} \left(\frac{2 \Delta h}{\Delta t_B - 400} \right) - (1 - K_{\Delta t}) K_{\Delta h} \Delta h \tag{53}$$

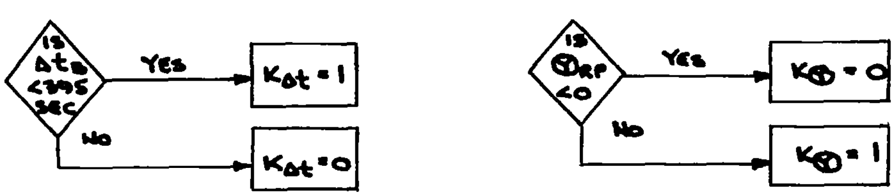
$$\Delta h = r_V - r_{NOM} \tag{54}$$

$$\theta_{REF} = (1 - K_{\Theta}) \left[\sin^{-1} \frac{\frac{GM}{r_V} - V_H^2}{r_V (T/m)} \right] \tag{55}$$

$$r_{NOM} = r_p \left[1 - K_{\Theta} + K_{\Theta} \left(\frac{1/e + 1}{1/e + \cos \Theta_{RP}} \right) \right] \tag{56}$$

$$\gamma_{NOM} \approx \tan \gamma_{NOM} = K_{\Theta} \left(\frac{\sin \Theta_{RP}}{1/e + \cos \Theta_{RP}} \right) \tag{57}$$

The additional logic terms used in equations 51, 53, 55, 56, and 57, $K_{\Delta t}$ and K_{Θ} were determined from:



2.5.2 Vertical Display Position and Velocity Drives

2.5.2.1 Ground Plane

The ground plane grid varied size as a function of vehicle altitude and translated as a function of the horizontal velocity components parallel and normal to the reference orbital plane. Because of a limitation on digital-to analog conversion capabilities, and since the altitude variations involved in this simulation were small compared to the nominal altitude, the altitude drive signal for the ground plane grid was approximated using the altitude error term of equation 54 and a nominal bias:

$$h_{DIS} = \Delta h + 1.823 \times 10^{6} \text{ feet} . \tag{58}$$

The velocity drives were:

$$V_{\parallel_{DIS}} = \dot{X}_o \tag{59}$$

$$V_{\perp_{DIS}} = \dot{Y}_o . \tag{60}$$

2.5.2.2 Pathway

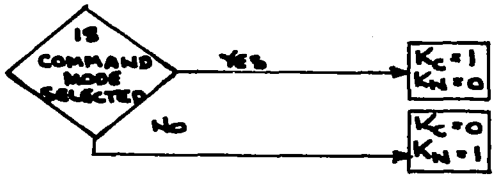
The pathway position and width were functions of vehicle lateral and vertical displacements from the nominal path and display mode conditions:

$$\Delta Y_{DIS} = K_N Y_P \tag{61}$$

$$\Delta h_{DIS} = K_N |\Delta h|_{ABS} \tag{62}$$

$$K_{h_{DIS}} = K_N \frac{\Delta h}{|\Delta h|_{ABS}} + K_C . \tag{63}$$

The logic terms, K_C and K_N, in equations 61-63 and 45, 47, and 48 were functions of the selected display mode, ATTITUDE or COMMAND ATTITUDE.

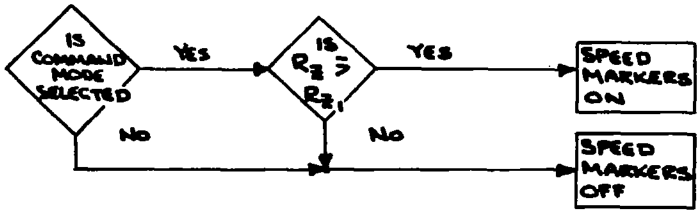


The motion of the tarstrips on the pathway was a function of vehicle velocity. Although there could be some difference in this velocity between the two display mode conditions, $\dot{X}_0$ and V for ATTITUDE and COMMAND ATTITUDE, respectively, the difference was negligible for this situation. As a result, and since conversion space was limited, $\dot{X}_0$ was used in both modes:

$$V_{PATH} = \dot{X}_0 \tag{64}$$

The speed markers along the pathway translated as a function of the velocity error and were displayed only in the COMMAND display mode. Two methods were available for "on-off" control the speed markers. In each case the speed markers were turned on automatically as a function of range, corresponding to a preselected time interval prior to thrust initiation, providing COMMAND mode was selected.

In the first, simpler method, the velocity error was displayed as zero (no speed marker motion), until the thrust initiation command was displayed, at which time the speed marker motion indicated the vehicle velocity differential which was to be corrected. The "on-off" control involved no more than the "on" command, automatically with range, then staying "on" as long as COMMAND display mode remained selected. With this method, the thrust termination indication was no more than observation of the speed marker motion slowing to a halt, with subsequent increase in rate in the reverse direction, if thrust was not terminated on schedule. The logic diagram for this "on-off" method is:



where $$R_Z = r_E \Theta_{RP} \; . \qquad (65)$$

The second, and more complex method, provided a means for alerting the pilot to the impending thrust initiation requirement with definite command indications for both thrust initiation and termination. With this method the speed markers were automatically turned off and back on five times prior to thrust initiation, the final one being the initiation command. The timing of these off-on commands to the speed marker control was fully adjustable. The thrust termination command indication consisted of turning off the speed markers when the computed velocity error had decreased to zero. An example of the timing of the speed marker on-off control used in the simulation was as follows:

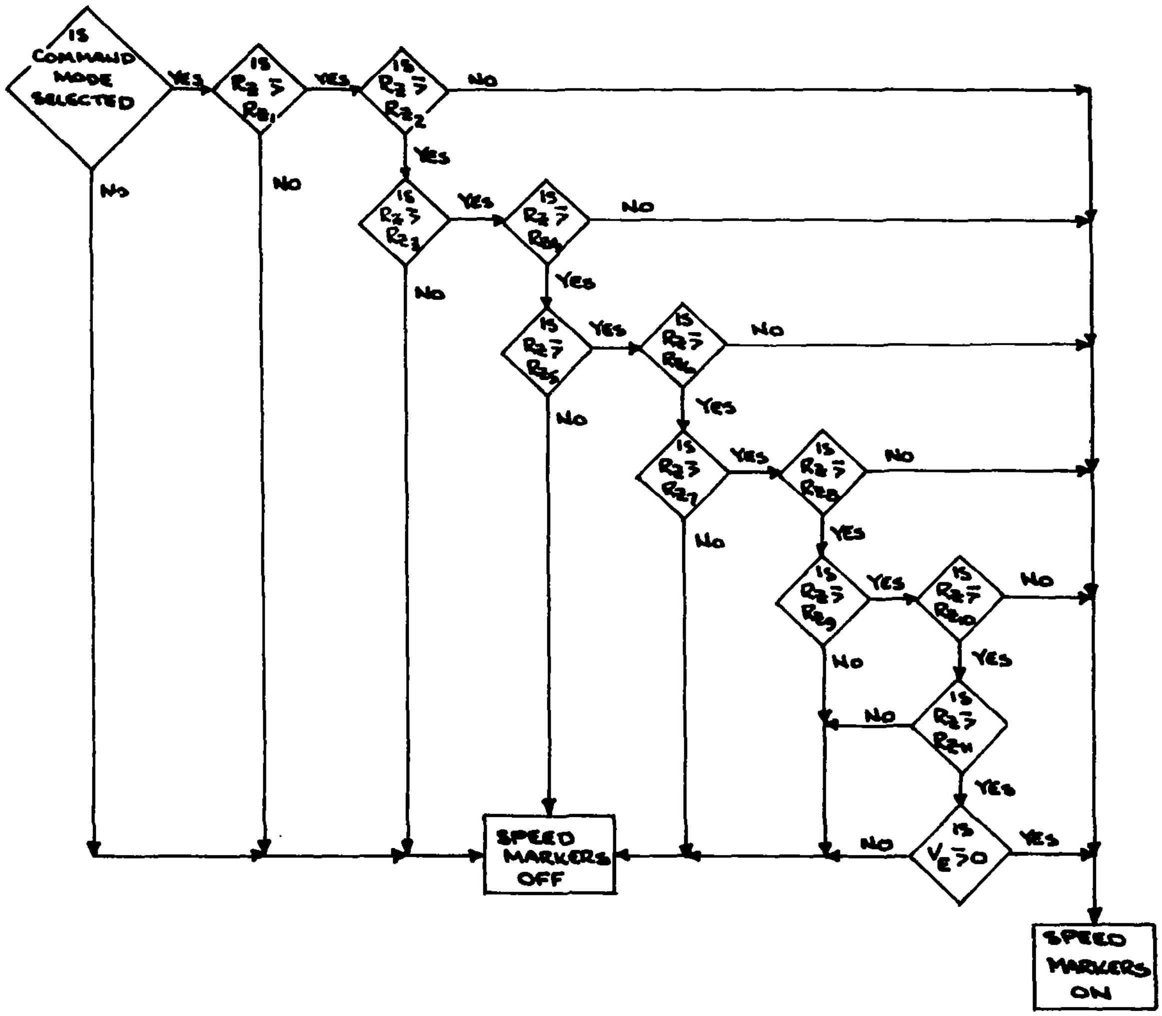
COMMAND Display Mode Selected - Speed Markers Off

Thrust initiation minus 20 sec.	- Speed Markers	On
" " " 10 "	- " "	Off
" " " 9.5 "	- " "	On
" " " 8 "	- " "	Off
" " " 7.5 "	- " "	On

Thrust initiation minus 6 sec.	- Speed Markers	Off
" " " 5.5 "	- " "	On
" " " 4 "	- " "	Off
" " " 3.5 "	- " "	On
" " " 2 "	- " "	Off
" " " 0.3 "	- " "	On and velocity error from zero to max.

Thrust termination minus 0.3 sec. - Velocity error decreased to zero, followed by speed markers off.

In this example, it should be noted that the thrust initiation and termination command indications were displayed 0.3 seconds prior to the required action as an allowance for pilot response. This lead time capability was also built into the velocity error computation so that it could indicate zero at a preselected time prior to attaining the required velocity. The logic diagram for this latter "on-off" method of speedmarker control was:



The range functions in the speedmarker logic diagrams (R_{Z_1} common to both) were time based, the times being preset as desired:

$$R_{Z_1} = R_{Z_I} + \dot{x}_o \Delta t_1 \quad (66)$$

$$R_{Z_2} = R_{Z_I} + \dot{x}_o \Delta t_2 \quad (67)$$

$$R_{Z_3} = R_{Z_I} + \dot{x}_o \Delta t_3 \quad (68)$$

$$R_{Z_4} = R_{Z_I} + \dot{x}_o \Delta t_4 \quad (69)$$

$$R_{Z_5} = R_{Z_I} + \dot{x}_o \Delta t_5 \quad (70)$$

$$R_{Z_6} = R_{Z_I} + \dot{x}_o \Delta t_6 \quad (71)$$

$$R_{Z_7} = R_{Z_I} + \dot{x}_o \Delta t_7 \quad (72)$$

$$R_{Z_8} = R_{Z_I} + \dot{x}_o \Delta t_8 \quad (73)$$

$$R_{Z_9} = R_{Z_I} + \dot{x}_o \Delta t_9 \quad (74)$$

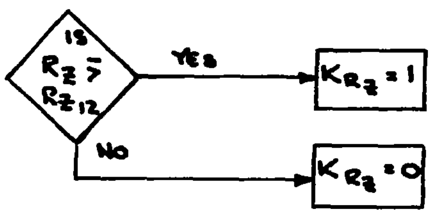
$$R_{Z_{10}} = R_{Z_I} + \dot{x}_o \Delta t_{10} \quad (75)$$

$$R_{Z_{11}} = R_{Z_I} + \dot{x}_o \Delta t_{11} \quad (76)$$

The velocity error computation for either method of speed marker control was:

$$V_E = K_{R_Z} \left[V_{NOM} - V + K_E \Delta t_A \left(T/m \right) \right] \quad (77)$$

with the logic term K_{R_Z} coming from:



where $$R_{z_{12}} = R_{z_I} + \dot{x}_0 \Delta t_{12} \tag{78}$$

and with $$V_{NOM} = V_p(1 - K_\Theta) + K_\Theta\left[\frac{GM}{r_{NOM}}\left(2 - \frac{1/e - e}{1/e + \cos\Theta_{RP}}\right)\right]^{1/2}. \tag{79}$$

The preset time constants, for the example shown for the latter method of on-off speedmarker control, had the following values

Δt_1 = -20 sec.

Δt_2 = -10 "

Δt_3 = -9.5 "

Δt_4 = -8 "

Δt_5 = -7.5 "

Δt_6 = -6

Δt_7 = -5.5 "

Δt_8 = -4 "

Δt_9 = -3.5 "

Δt_{10} = -2 "

Δt_{11} = -0.3 "

Δt_{12} = -0.3 "

Δt_A = -0.2 "

(Since T/M was used in equation 77 with Δt_A to compute an equivalent velocity change and dV/dt was only about 2/3 of T/M near termination, Δt_A was adjusted so that computed velocity change corresponded to a lead of 0.3 sec.)

2.5.3 <u>Horizontal Display</u>

Three separate presentations were combined on the horizontal television display (Figure I-A-3) and implemented using the setup in Figure I-A-4 as follows:

2.5.3.1 Vehicle Horizontal Situation

The horizontal situation display was implemented using a 5-inch diameter CRT and a stepping switch to generate the individual traces. The rectangular coordinates plotted on this scope were lateral, out-of-plane, versus longitudinal,

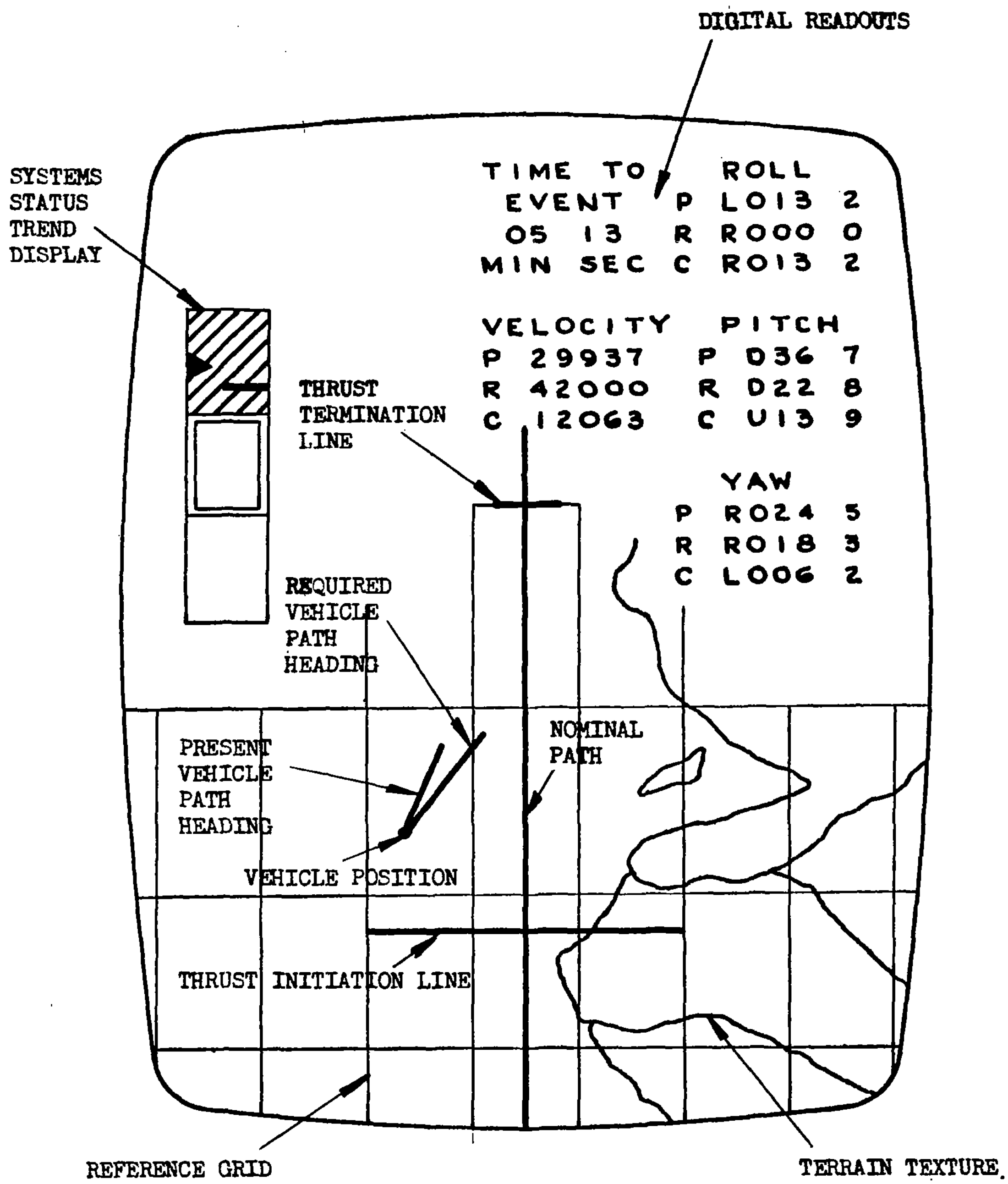


FIGURE I-A-3 HORIZONTAL DISPLAY, COMMAND MODE, STATUS TREND SELECTED

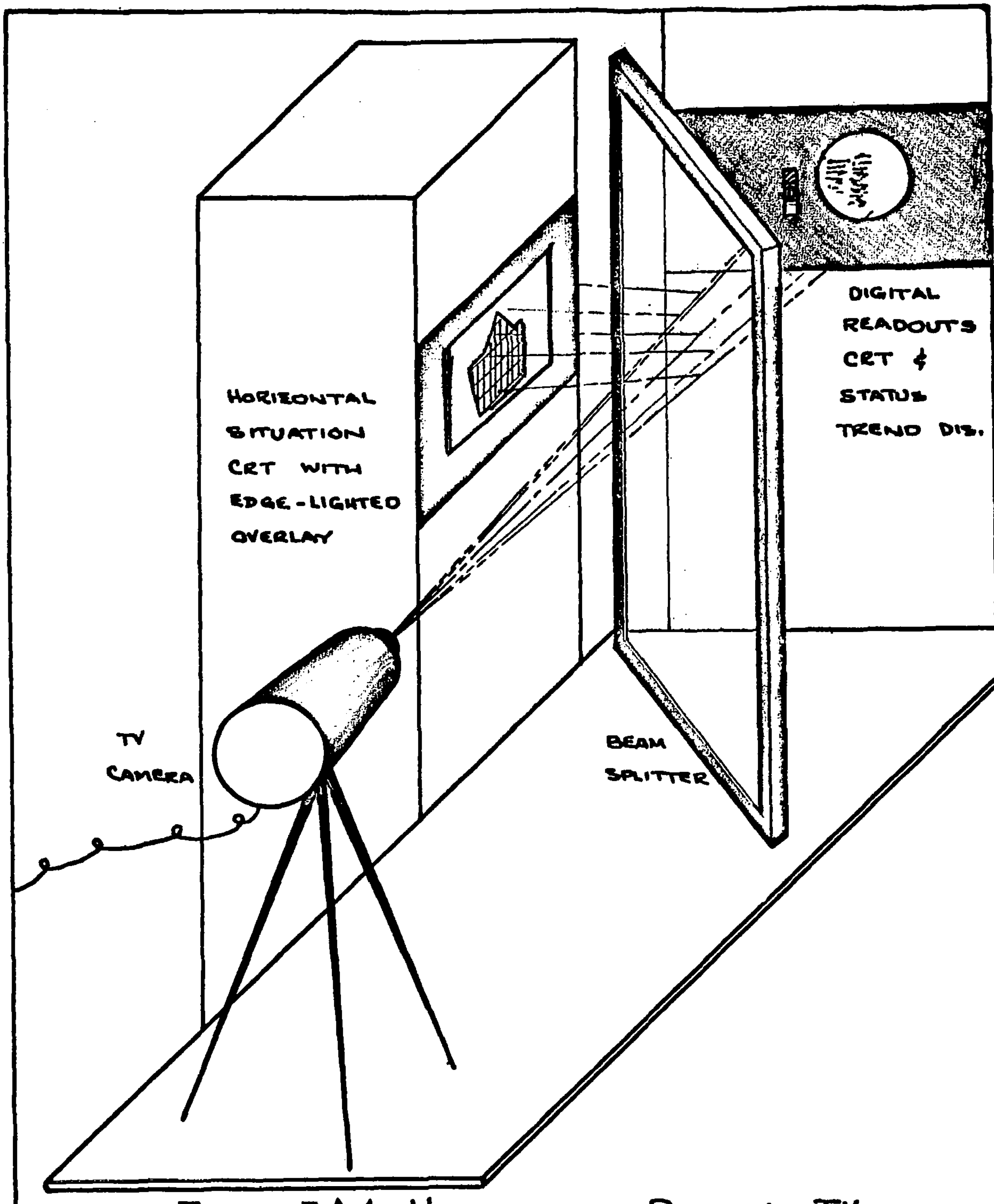


FIGURE I-A-4 HORIZONTAL DISPLAY, TV CAMERA ARRANGEMENT in-plane, range as projected into the inertially oriented Y_P-Z_P plane, local horizontal plane at nominal thrust termination.

The lateral, Y_P, range inputs were scaled such that 2×10^5 feet produced a lateral scope deflection of one inch with zero on the vertical centerline of the CRT. The longitudinal, Z_P, range inputs were relative to the nominal thrust termination position and were scaled for 5×10^6 feet per inch of vertical scope deflection. Zero longitudinal range was displayed 1.75 inches above the CRT lateral centerline. The reference plane, nominal path line was generated as a vertical, longitudinal, line with a fixed position and length, at zero lateral displacement (CRT centerline) with a length of 4.5 inches ($\pm$2.25 inches from the center), an equivalent Z_P range of 22.5×10^6 feet. The present path line, and the reference plane line were the only horizontal situation display parameters during ATTITUDE display mode operation. They were generated from present vehicle position and flight path heading information with the CRT coordinates for each end of the line being computed. This computation was performed in the analog computer as follows:

$$Y_{V_{CRT}} = Y_P \times (\text{SCALE FACTOR})$$

$$Z_{V_{CRT}} = Z_P \times (\text{SCALE FACTOR}) + (\text{OFFSET})$$

$$Y_{H_{CRT}} = Y_{V_{CRT}} + (\text{LINE LENGTH} @ \psi_H = 0) \sin \psi_H \frac{(Y_P \text{ SCALE FACTOR})}{(Z_P \text{ SCALE FACTOR})}$$

$$Z_{H_{CRT}} = Z_{V_{CRT}} + (\text{LINE LENGTH} @ \psi_H = 0) \cos \psi_H$$

$$\tan \psi_H = \dot{Y}_0 / \dot{X}_0$$

Assuming ψ_H is a small angle, such that the sine of the angle equals the tangent and the cosine is unity, and, letting $\dot{X}_0$ be constant at 25,000 feet per second (which tended to amplify the displayed angle as velocity increased and the required flight path angle approached zero), also using a line length at $\Psi_H = 0$ of 0.5 inch, and applying the scale factors and offset, the equations for these CRT deflections in inches were as follows:

$$Y_{V_{CRT}} = 5 Y_P \times 10^{-6} \tag{80}$$

$$Z_{V_{CRT}} = 1.75 + 2 Z_P \times 10^{-7} \tag{81}$$

$$Y_{H_{CRT}} = Y_{V_{CRT}} + 5 \dot{Y}_O \times 10^{-4} \tag{82}$$

$$Z_{H_{CRT}} = Z_{V_{CRT}} + 0.5 \tag{83}$$

Three additional lines were displayed during COMMAND ATTITUDE display mode operation. A lateral line, 2 inches length, centered on the vertical centerline, was generated to denote the longitudinal position for thrust initiation. The vertical (longitudinal) displacement of this line on the CRT was determined from the preset values of R_{Z_I} and orbital radius at the thrust initiation point:

$$Z_{I_{CRT}} = 1.75 + 2 r_{V_I} \sin\left(\frac{R_{Z_I}}{r_E}\right) \tag{84}$$

The position for thrust termination was depicted by a second lateral line, this one 0.4 inch long, positioned 1.75 inches above CRT centerline (Zp and R_Z values of zero). The rectangular coordinates for one end of the command flight path heading line were the same as those for the vehicle position end ($Y_{V_{CRT}}$ and $Z_{V_{CRT}}$) of the present heading line. The coordinates for the other end were computed in a similar manner as equations 82 and 83 except for the length of the line at zero heading being 0.625 inches and the use of $\dot{Y}_{O_{REF}}$:

$$Y_{C_{CRT}} = Y_{V_{CRT}} + 6.25 \dot{Y}_{O_{REF}} \times 10^{-4} \tag{85}$$

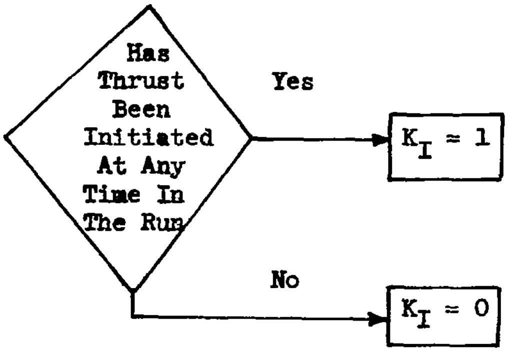
$$Z_{C_{CRT}} = Z_{V_{CRT}} + 0.625 \tag{86}$$

2.5.3.2 Digital Readouts

The digital readout parameters which were common to both display mode conditions were present velocity which was equal to V and time to event, required velocity, and velocity change which were computed as follows:

$$t_{TG} = (1-K_I)\,\frac{(R_{Z_I}-R_Z)}{\dot{X}_0} + K_I\,\frac{(V_{NOM}-V)}{38+.014\,\Delta t_B} \qquad (87)$$

where the logic term K_I was defined by



and the denominator term, $(38 + .014\ \Delta t_B)$, was an approximation for dV/dt,

$$V_{REQ} = K_N V + K_C V_{NOM} \qquad (88)$$

$$V_{CORR} = V_{REQ} - V \qquad (89)$$

The attitude parameters which were part of the digital readouts during COMMAND mode operation were: the present roll, pitch, and yaw angles which were equal to ϕ_3, θ_3, and Ψ_3, respectively; the required roll, pitch, and yaw angles which were equal to zero, θ_C, and Ψ_C, respectively; and the roll, pitch, and yaw attitude changes which were determined from:

$$\phi_{CORR} = -\phi_3 \qquad (90)$$

$$\theta_{CORR} = \theta_C - \theta_3 \qquad (91)$$

$$\Psi_{CORR} = \Psi_C - \Psi_3 \qquad (92)$$

2.5.3.3 Vehicle Subsystems Status-Trend

The status-trend display; a Series 360, Industrial Electronic Engineers, rear-projection readout; appeared on the horizontal TV screen only in conjunction with pilot selection of STATUS-TREND. The indicator positions on this display were artifically produced by illumination of one of the twelve individual film strips in the display unit, each film strip providing a different combination of the two indicator positions. The selection of the indicator position film strip for each operation of the status-trend display was made by the digital computer from a random order storage of the twelve combinations. Each selection was independent of all others displayed, there being no intended relationship to previous or subsequent selections.

2.6 MOVING BASE DRIVES

The moving base of the simulator cockpit was driven as a function of the computed vehicle body axis angular and translational accelerations. The angular accelerations - $\dot{p}$, $\dot{q}$, and $\dot{r}$ - drove the primary roll, pitch, and yaw motions, the translational acceleration - $\Delta\ddot{X}_B$ - producing displacement of the outer pitch drive:

Roll displacement radians = $\left[\frac{0.3\,\dot{p}}{2S+1}\right]_{\lim \pm .349\ \text{rad}}$ (93)

Inner pitch displacement, radians = $\left[\frac{0.3\,\dot{q}}{2S+1}\right]_{\lim \pm .174\ \text{rad}}$ (94)

Yaw displacement, radians = $\left[\frac{0.3\,\dot{r}}{2S+1}\right]_{\lim \pm .174\ \text{rad}}$ (95)

Outer pitch displacement, radians = $\left[\frac{0.031\,\Delta\ddot{X}_B}{2S+1}\right]_{\lim \pm 1.57\ \text{rad}}$ (96)

2.7 DATA RECORDING PARAMETER COMPUTATION

A number of data recording parameters required computation in addition to those presented in Sections 2.1 through 2.6. These were:

$$\epsilon_\psi = -\psi_{CORR} \tag{97}$$

$$\epsilon_\theta = -\theta_{CORR} \tag{98}$$

$$\epsilon_{\psi_{ABS}} = \frac{1}{\Delta t_B} \int_0^t |K_E \epsilon_\psi|_{ABS} \, dt \tag{99}$$

$$\epsilon_{\theta_{ABS}} = \frac{1}{\Delta t_B} \int_0^t |K_E \epsilon_\theta|_{ABS} \, dt \tag{100}$$

$$\epsilon_{\phi_{ABS}} = \frac{1}{\Delta t_B} \int_0^t |K_E \phi_B|_{ABS} \, dt \tag{101}$$

$$\Delta V = \int_0^t K_E (T/m) \, dt \tag{102}$$

$$\Delta p_s = \int_0^t |\Delta \dot{p}_s|_{ABS} \, dt \tag{103}$$

$$\Delta q_s = \int_0^t |\Delta \dot{q}_s|_{ABS} \, dt \tag{104}$$

$$\Delta r_s = \int_0^t |\Delta \dot{r}_s|_{ABS} \, dt \tag{105}$$

$$\epsilon_V = -V_{CORR} \tag{106}$$

$$\epsilon_\gamma = \gamma - \gamma_{NOM} \tag{107}$$

3.0 COMPUTER DATA INPUTS

The data inputs for the computer program during the First evaluation simulation program were as shown in Tables I-A-1 & 2. Table I-A-1 presents values of those parameters and constants which were independent of initial conditions. Table I-A-2 lists the parameter values for the 15 initial condition situations which were programmed for use in the simulation.

TABLE I-A-1

SIMULATION CONSTANTS - FIRST EVALUATION

Parameter	Value
e	1.85070416
GM	$1.407690367 \times 10^{16}$ ft^3/sec^2
I_{sp}	850 sec.
$K_{\dot{h}}$, $K_{\dot{y}_o}$	0.002 rad/ft/sec
$K_{\Delta h}$, K_{y_p}	2^{-6} per sec.
K_{p_1}	0.556
K_{p_2}	-0.0111
$K_{p_{3,4}}$	0.0056
K_{q_1}	0.0500
K_{q_2}	-0.0100
$K_{q_{3,4}}$	0.0050
K_{r_1}	-0.1053
K_{r_2}	-0.0105
$K_{r_{3,4}}$	0.0053
K_{θ_A}, K_{ψ_A}, K_{ϕ_A}	2.0 per sec.

TABLE I-A-1

SIMULATION CONSTANTS - FIRST EVALUATION (Cont'd)

Parameter	Value
$\Delta \dot{q}_{E_o}$	2^{-7} rad/sec^2
$\Delta \dot{r}_{E_o}$	0
$d\dot{q}_E/d\,\frac{T}{M}$	-2^{-11} rad/ft
$d\dot{r}_E/d\,\frac{T}{M}$	2^{-12} rad/ft
r_E	20.926083×10^6 ft.
r_P	22.748918×10^6 ft.
Δt_A	0
Δt_1	-20 sec.
Δt_2	-10 sec.
Δt_3	-9.5 sec.
Δt_4	-8 sec.
Δt_5	-7.5 sec.
Δt_6	-6 sec.
Δt_7	-5.5 sec.
Δt_8	-4 sec.
Δt_9	-3.5 sec.
Δt_{10}	-2 sec.
$\Delta t_{11,12}$	0
T/M_o	32.2 ft/sec^2
V_P	42,000 fps

COND No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	COMPUTER I.C. INPUTS														
X_P FT	11,374,459	11,374,366	11,374,366	11,335,491	11,335,398	11,335,398	11,413,556	11,413,463	11,413,463	11,466,392	11,466,300	11,466,300	11,282,258	11,282,164	11,282,164
Y_P FT	0	92,068.40	-92,068.40	0	91,752.97	-91,752.97	0	92,384.86	-92,384.86	0	92,003.67	-92,003.67	0	92,132.07	-92,132.07
Z_P FT	-19,701,141	-19,700,980	-19,700,980	-19,633,645	-19,633,484	-19,633,484	-19,768,858	-19,768,697	-19,768,697	-19,860,373	-19,860,213	-19,860,213	-19,541,444	-19,541,281	-19,541,281
$\dot{X}_P$ FPS	21,542.88	21,542.77	21,542.77	21,717.16	21,717.04	21,717.04	21,367.94	21,367.46	21,367.46	21,412.01	21,411.90	21,411.90	21,675.41	21,675.29	21,675.29
$\dot{Y}_P$ FPS	0	42.6794	-42.6794	0	43.6424	-43.6424	0	41.7190	-41.7190	0	42.3091	-42.3091	0	43.0597	-43.0597
$\dot{Z}_P$ FPS	12,437.79	12,437.92	12,437.92	12,305.05	12,305.18	12,305.18	12,568.43	12,568.34	12,568.34	12,263.66	12,263.76	12,263.76	12,612.88	12,613.01	12,613.01
l_1 2 3	.742404 .519841 -.422620	.742404 .519841 -.422620	.742404 -.519841 -.422620	.742404 -.519841 -.422620	.043580 .498095 .866030	.043580 .498095 .866030	.043580 -.498095 .866030	.043580 -.498095 .866030	.742404 .519841 -.422620	.742404 .519841 -.422620	.742404 -.519841 -.422620	.742404 -.519841 -.422620	.043580 .498095 .866030	.043580 .498095 .866030	.043580 -.498095 .866030
m_1 2 3	-.373535 .844850 .383025	-.521487 .052319 -.851650	.521487 .052319 .851650	.373535 .844850 -.383025	-.994166 -.063977 .086825	.075483 .862730 -.500000	-.075483 .862730 .500000	.994166 -.063977 -.086825	-.373535 .844850 .383025	-.521487 .052319 -.851650	.521487 .052319 -.851650	.373535 .844850 -.383025	-.994166 -.063977 .086825	.075483 .862730 -.500000	-.075483 .862730 .500000
n_1 2 3	.556161 -.126494 .821398	-.420584 .852655 .309976	-.420584 -.852655 .309976	.556161 .126494 .821398	.098652 -.864761 .492405	-.996190 .087160 0	-.996190 -.087160 0	.098652 .864761 .492405	.556161 -.126494 .821398	-.420584 .852655 .309976	-.420584 -.852656 .309976	.556161 .126494 .821398	.098652 -.864761 .492405	-.996190 .087160 0	-.996190 -.087160 0
R_{ZI} N.MI.	-2248.5	-2250.9	-2250.9	-2248.5	-2250.2	-2250.2	-2250.0	-2251.9	-2251.9	-2212.1	-2215.3	-2215.3	-2300.9	-2301.8	-2301.8
	I.C. EQUIVALENTS														
r_V FT	22,748,918			22,670,981			22,827,111			22,932,784			22,564,516		
V FPS	24,875.58			24,960.95			24,790.20			24,675.33			25,078.04		
$\dot{h}$ FPS	0			202.10			-200.60			85.36			-85.36		
Φ_{RD} DEG	0	0.232	-0.232	0	0.232	-0.232	0	0.232	-0.232	0	0.230	-0.230	0	0.234	-0.234
θ_S DEG	47.5	47.7	47.7	47.5	-46.6	-46.9	-46.7	-46.9	47.3	47.5	47.3	47.7	-46.7	-46.6	-46.6
ψ_S DEG	50.3	50.1	-50.1	-50.3	46.8	46.4	-46.6	-46.4	50.5	50.3	-50.5	-50.1	46.6	46.8	-46.8
ϕ_S DEG	50.1	-45.1	44.7	-50.1	56.4	-43.2	43.4	-56.8	50.3	-44.9	44.7	-49.9	56.6	-43.6	43.6
	APPROXIMATE CONDITIONS @ THRUST INITIATION														
r_{V_I} FT	22,748,918			22,748,918			22,748,918			22,948,918			22,548,918		
V_I FPS	24,875.58			24,875.58			24,875.58			24,657.84			25,095.25		
$\dot{h}_I$ FPS	0			218.70			-218.70			0			0		
Φ_{RDI} DEG	0	0.252	-0.252	0	0.252	-0.252	0	0.252	-0.252	0	0.250	-0.250	0	0.254	-0.254

NOTE: I.C. VALUES FOR BODY RATES - p, q, & r - WERE ZERO FOR ALL 15 CONDITIONS.

TABLE I-A-2 INITIAL CONDITIONS - FIRST EVALUATION

4.0 PROGRAM CHANGES DURING OPERATION

Several changes to the simulation program were effected during the basic experimental test phase and for a subsequent brief qualitative evaluation of different vertical display drive methods.

4.1 EXPERIMENTAL TEST PHASE

Changes to the basic experimental runs involved: the $K_{Ⓥ}$ logic in the attitude command computations, the velocity error lead time (Δt_A), the speed marker logic timing (Δt_{11} and Δt_{12}), generation of the vertical display pitch and heading error drive signals, and task loading switch lighting and nomenclature.

4.1.1 $K_{Ⓥ}$ Logic

Prior to initiation of the experimental runs it was noticed that the step change in pitch command at the nominal thrust termination longitude resulting from θ_{REF} going to zero, as required to change from the nominal circular orbit to the hyperbolic path, provided a cue which coincided too closely with the primary thrust termination command indication, speed markers "off." To prevent possible response by the test subjects to this cue rather than the speed marker indication, the $K_{Ⓥ}$ logic was disabled such that $K_{Ⓥ}$ remained constant at zero and the nominal circular orbital path was maintained past the nominal point for insertion into the hyperbolic path.

4.1.2 Velocity Error Lead Time

The value of the lead time, Δt_A, in the velocity error (V_E) computation for thrust termination was changed twice during the experimental runs in attempting to compensate for an average subject response time. The initial value in Table I-A-1 of zero was first changed to -0.7 sec. and later to -0.5 sec. where it remained thereafter.

4.1.3 Speed Marker Timing

The preset time values for indication of the ignition command with the speed markers and for the corresponding step input in the velocity error, Δt_{11} and Δt_{12}, respectively, initially were zero as shown in Table I-A-1 were both changed early in the experimental run phase to -0.6 sec., to allow for subject response time.

4.1.4 Vertical Display Pitch and Heading Errors

Prior to the final day of experimental runs the analog computer setup was revised to eliminate the servo resolvers which had been used for generating the sine and cosine values of $\theta_{E_{DIS}}$ and $\Psi_{E_{DIS}}$ in order to attain smoother drive signals for the vertical display. The new approach assumed small angle relationships wherein the angular values of $\theta_{E_{DIS}}$ and $\Psi_{E_{DIS}}$ in radians were used for the sine inputs and the cosine inputs were set constant at unity. In the process of making this revision a scaling error was discovered which previously had been present in the displayed values of $\theta_{E_{DIS}}$ and $\Psi_{E_{DIS}}$. This error was such that the displayed values previous to the change were greater than intended by a factor of 1.7453. This error was corrected at the time of the revision.

4.1.5 Task Loading

In the process of conducting the experimental runs it was determined that the use of the red-lighted WARNING switch-light resulted in some pilot response to the automatic task loading alerts at the expense of the primary guidance and control task. To correct this tendency the amber illuminated CAUTION switchlight was substituted for the red illuminated WARNING switchlight.

4.2 VERTICAL DISPLAY DRIVE VARIATIONS

On completion of the basic experimental runs which were all performed with the vertical display configured as previously described, additional methods for driving the vertical display in the COMMAND mode were briefly evaluated. These included two different approaches for orientation of the background scene (horizon, ground plane, and starfield). This involved changes in the pitch and/or yaw input signals, the roll input signal remaining as the sine and cosine of ϕ_{DIS} as previously described. In the first approach present flight path orientation with a higher sensitivity was substituted for vehicle attitude, i.e.:

$$\Psi_{DIS} = K_{G1}\left[K_N\Psi_3 + 4K_C\Psi_H\right] \tag{108}$$

$$\theta_{DIS} = K_{G2}\left[K_N\theta_3 + 2K_C\gamma\right] \tag{109}$$

In the other approach, only the pitch input signal was changed. In this case the pitch attitude relative to θ_{REF} was displayed:

$$\theta_{DIS} = K_{G2}\left[\theta_3 - K_C\theta_{REF}\right] \tag{110}$$

Two additional methods for driving the pitch and heading error inputs to the pathway were investigated. The first presented the relative orientation between the actual and nominal flight paths:

$$\Psi_{E_{DIS}} = \left[K_{G4}\ (K_N\Psi_E + 4K_C\Psi_H)\right] \text{ limit} \pm 20^\circ \tag{111}$$

$$\theta_{E_{DIS}} = \left[K_{G5}\ K_C\ (2\gamma)\right] \text{ limit } {}^{-12^\circ}_{+15^\circ} \tag{112}$$

The other method presented the relative orientation between the actual and commanded flight paths:

$$\Psi_{E_{DIS}} = \left[K_{G4}\left\{K_N\Psi_E - K_CK_{\dot{Y}_O}\ (\dot{Y}_{O_{REF}} - \dot{Y}_O\right\}\right] \text{ limit} \pm 20^\circ \tag{113}$$

$$\theta_{E_{DIS}} = \left[-K_{G_5}\ KC\ K_{\dot{h}}\ (\dot{h}_{REF} + \dot{Z}_O)\right] \text{ limit } {}^{-12^\circ}_{+15^\circ} \tag{114}$$

In addition, the simulation was revised so that the pathway could be driven with altitude error and lateral offset during COMMAND mode operation as well as ATTITUDE mode:

$$\Delta Y_{DIS} = Y_P \tag{115}$$

$$\Delta h_{DIS} = |\Delta h|_{ABS} \tag{116}$$

$$K_{hDIS} = \frac{\Delta h}{|\Delta h|_{ABS}} \tag{117}$$

When evaluating these revised display methods the $K_{\textcircled{Y}}$ logic was enabled, functioning in the attitude command computations as described in Section 2.5.1.2 of this report.

APPENDIX I-B

PILOT QUESTIONNAIRE

NASA DISPLAY-CONTROL STUDY
PILOT REPORT

1. GENERAL PANEL LAYOUT

1A. Could you obtain information from both the Vertical Display and the Horizontal Display simultaneously?

RATING SCALE	GROUP (MEAN)	INDIVIDUAL	
(1) - No	(1.67)	1. (1)	4. (2)
(2) - To some degree		2. (2)	5. (3)
(3) - Yes		3. (1)	6. (1)

1B. When viewing the Vertical Display or the Horizontal Display, could you scan the Warning Panel to the right or the System Panel to the left?

RATING SCALE	GROUP (MEAN)	INDIVIDUAL	
(1) - No	(2.67)	1. (3)	4. (2)
(2) - To some degree		2. (3)	5. (3)
(3) - Yes		3. (3)	6. (2)

1C. From a pilot's standpoint, what struck you as particularly good about the panel layout?

1. Vertical situation display and lights.
2. No comment.
3. Easy to reach.
4. Satisfactorily fulfilled requirements of mission.
5. Easy reach and accessibility.
6. Vertical Attitude Display clarity.

1D. What struck as particularly objectionable about the panel layout?

1. Arm crossover to null task loading.
2. (Same) Plus multi responses for task loading.
3. Status-trend display on horizontal situation display.
4. Horizontal Situation Display not easily visible during thrust (due to gondola gross pitch).
5. Same as 1.
6. Same as 1.

1E. Rate the panel layout.

RATING SCALE	GROUP (MEAN)	INDIVIDUAL
(1) - Poor (2) - Fair (3) - Good	(3)	1. through 6. (3)

2. VERTICAL DISPLAY - ATTITUDE /ATTITUDE COMMAND

2A. In the Situation Mode, rate ease of obtaining vehicle orientation information as the flight began:

RATING SCALE	GROUP (MEAN)	INDIVIDUAL
(1) - Difficult (2) - Intermediate (3) - Easy	(3)	1. through 6.(3)

2B. How does this presentation compare with the two methods below in presentation of vehicle attitude?

Visual reference.

RATING SCALE	GROUP (MEAN)	INDIVIDUAL
(1) - No comparison (2) - Not as good as VFR (3) - Equal to VFR	(2.58)	1. (3) 4. (3) 2. (2) 5. (2) 3. (3) 6. (3-2)

A three-axis ball

RATING SCALE	GROUP (MEAN)	INDIVIDUAL
(1) - Inferior to ball (2) - As good as ball (3) - Superior to ball	(2.90)	1. (3) 4. (no basis of comparison) 2. (3) 5. (3) 3. (3) 6. (3-2)

2C. In the Attitude Mode, rate ease of obtaining nominal path information - its relationship to your vehicle:

RATING SCALE	GROUP (MEAN)	INDIVIDUAL
(1) - Difficult (2) - Intermediate (3) - Easy	(2.83)	1. (3) 4. (2) 2. (3) 5. (3) 3. (3) 6. (3)

2D. In your opinion, is this a feasible way of presenting orbital situation information?

Yes (all subjects).

2E. In the Command Mode, rate ease of following the attitude command profile:

RATING SCALE	GROUP (MEAN)	INDIVIDUAL	
(1) - Difficult.	(2.75)	1. (3)	4. (2)
(2) - Intermediate.		2. (3)	5. (3-2)
(3) - Easy.		3. (3)	6. (3)

2F. Any general comments on the vertical display?

1. Roll difficult to interpret.
2. Ground terrain unnecessary in command mode.
3. Same as 1.
4. Acclimation to "fly to" difficult.
5. Same as 1.

2G. Compare the attitude command information given you by the Space Analog with other attitude command displays you may be familiar with (such as the Lear 3-axis ball, etc.)

RATING SCALE	GROUP (MEAN)	INDIVIDUAL	
(1) - Inferior to other attitude command displays.	(2.63)	1. (3)	4.(no response)
(2) - Equal.		2. (2)	5.(no response)
(3) - Superior.		3. (3)	6.(no response)

IF YOU HAD BACKUP DIGITAL INFORMATION:

2H. To what extent did you use the numbers for attitude control of the vehicle?

RATING SCALE	GROUP (MEAN)	INDIVIDUAL
(1) - A great deal.	(1.67)	2. (1)
(2) - Some.		3. (3)
(3) - Very little.		6. (1)

3. VERTICAL DISPLAY-VELOCITY INFORMATION

3A. Rate the command velocity marker thrust initiation cue.

RATING SCALE	GROUP (MEAN)	INDIVIDUAL	
(1) - Poor.	(2.33)	1. (3)	4. (2)
(2) - Fair.		2. (2)	5. (2)
(3) - Good.		3. (3)	6. (2)

3B. Rate command velocity thrust termination cue.

RATING SCALE	GROUP (MEAN)	INDIVIDUAL	
(1) - Poor.	(2.00)	1. (3)	4. (2)
(2) - Fair.		2. (2)	5. (2)
(3) - Good.		3. (1)	6. (2)

3C. Rate these cues as to preference for thrust initiation countdown.

RATING SCALE

(1) - Poor.
(2) - Fair.
(3) - Good.

	GROUP (MEAN)	INDIVIDUAL					
		1.	2.	3.	4.	5.	6.
Vertical display command velocity markers.	(2.83)	(3)	(2)	(3)	(3)	(3)	(3)
Horizontal display initiation point.	(1.17)	(1)	(1)	(1)	(1)	(2)	(1)
(if you had this) Timer (on horizontal display).	(2.33)	(-)	(3)	(2)	(-)	(-)	(2)

3D. Rate these cues as to preference for thrust termination countdown:

RATING SCALE

(1) - Poor.
(2) - Fair.
(3) - Good

	GROUP (MEAN)	1.	2.	3.	4.	5.	6.
Vertical display command velocity markers.	(2.83)	(3)	(2)	(3)	(3)	(3)	(3)
Horizontal display initiation point.	(1.17)	(1)	(1)	(1)	(1)	(2)	(1)
(if you had this) Timer (on horizontal display).	(2.33)	(-)	(3)	(2)	(-)	(-)	(2)

4. HORIZONTAL DISPLAY - SITUATION/HEADING

4A. Rate the effectiveness of the horizontal display depiction of nominal path and vehicle position/path heading:

RATING SCALE	GROUP (MEAN)	INDIVIDUAL	
(1) - Poor.	(1.33)	1. (2)	4. (no rating)
(2) - Fair.		2. (1)	5. (1)
(3) - Good.		3. (1)	6. (2)

4B. How did you use vehicle heading and command heading in flying the injection maneuver (in relation to information received from the Vertical Display).

1. Not used.
2. No data (misunderstood question).
3. Not used.
4. Not used.
5. Used at command mode select.

IF YOU HAD BACKUP DIGITAL INFORMATION

5. DIGITAL READOUTS - VELOCITY

5A. To what extent did you use digital velocity information?

RATING SCALE	GROUP (MEAN)	INDIVIDUAL
(1) - Very little.	(1)	2. (1)
(2) - Some.		3. (1)
(3) - A great deal.		6. (1)

5B. Rank the following in descending order in which you used them:

	2.	3.	6.
Present velocity (P)	(2)	(2)	(-)
Required velocity (R)	(3)	(3)	(-)
Change in velocity (C)	(1)	(1)	(-)

6. SYSTEMS MONITORING DISPLAYS

6A. What do you think of a method like this for presenting system information vs. an array of constantly visible system parameter displays?

1. Like display, did not want to see information if system was functioning properly.
2. Preferred single parameter dials.
3. Acceptable, status-trend could be by light code.
4. Very good.
5. Same as 2.
6. Acceptable for ease of monitoring, but preferred numerical and trend information and more automatic operation.

6B. How much of a distraction was the system monitoring task for you?

RATING SCALE

(1) - Very distracting.
(2) - Moderately distracting.
(3) - No problem.

	GROUP (MEAN)	INDIVIDUAL 1.	2.	3.	4.	5.	6.
-Early in the flights.	(2.42)	(3)	(2)	(2)	(2-3)	(2)	(3)
-Late in the flights.	(2.42)	(2)	(2)	(3)	(2-3)	(3)	(2)

6C. How important did you consider the system monitoring task: Apportion your time in percentage between the two tasks as you recall it:

	GROUP (MEAN)	INDIVIDUAL 1.	2.	3.	4.	5.	6.
- During coast. Flight Management	(64.2%)	(25)	(70)	(50)	(70)	(90)	(80)
System Monitoring	(35.8%)	(75)	(30)	(50)	(30)	(10)	(20)
- During thrust. Flight Management	(84.2%)	(50)	(90)	(90)	(95)	(90)	(90)
System Management	(15.8%)	(50)	(10)	(10)	(5)	(10)	(10)

7. WOULD YOU BE WILLING TO SERVE AS A PILOT IN A FUTURE SIMULATION LIKE THIS?

Yes (all subjects).

8. ANY COMMENTS OR CRITICISMS OF THE SIMULATION OR OF ANY PANEL FEATURE?

1. None.
2. Replace attitude trim potentiometers with "beep" trim; place as on aircraft (pitch and roll on stick, yaw on left console). Only digital readouts required are: roll, right-left; pitch, up-down; yaw, left-right; and their values; and time-to-go. Yaw profile should be less abrupt.
3. Better roll information needed. Digital information should be more legible (larger).
4. Horizontal display not necessary for this maneuver.
5. Need analog display of trim displacement, or some way of determining this. No way of gauging amount to put on in present setup.
6. A better horizontal display presentation might be of some use. Thrust ignition/termination cue should be positive light onset.

APPENDIX II-A

SECOND EVALUATION - SIMULATION EQUATIONS

The implementation of the Second Evaluation Simulator program was as described in Appendix I-A with revisions to the display mode nomenclature, display drive signals, and data recording parameters.

1.0 DISPLAY DRIVE SIGNALS

1.1 Vertical Display

In the Second Evaluation the vertical display had two modes of operation - SPACE VEHICLE ATTITUDE AND SPACE VEHICLE PATH. The ATTITUDE mode was identical to the ATTITUDE mode of the First Evaluation with the PATH mode replacing the previously used COMMAND ATTITUDE mode.

The display mode logic terms in the equations, K_N and K_C, which were formerly associated with ATTITUDE and COMMAND ATTITUDE mode operation, respectively, in the First Evaluation, were used for ATTITUDE and PATH mode operation, respectively, in the Second.

The vertical display angular drives were essentially as defined in Section 4.2 of Appendix I-A:

$$\psi_{DIS} = K_{G_1} \left[K_N \psi_3 + 4 K_C \psi_H \right] \quad (1)$$

$$\theta_{DIS} = K_{G_2} \left[K_N \theta_3 + 2 K_C \gamma \right] \quad (2)$$

$$\psi_{EDIS} = K_{G_A} \left[K_N \psi_E + K_{\psi_H} K_C \psi_H \right] \quad (3)$$

$$\theta_{EDIS} = K_{G_S} \left[K_\gamma K_C (\gamma - \gamma_{NOM}) \right] \quad (4)$$

The values of ψ_{EDIS} and θ_{EDIS} were originally limited in the Second Evaluation to $\pm$ 20° and + 15° and - 12°, respectively; these limits were later removed.

The gains K_{ψ_H} and K_γ were adjusted such that full screen displacements of the path tip were obtained in the PATH mode for values of ψ_H of $\pm$ 0.4 deg. and $(\gamma - \gamma_{NOM})$ of $\pm$ 1.4 deg.

In the ATTITUDE mode, full screen path tip displacements were obtained for values of ψ_E of ± 19.1 deg. and θ_3 of ± 8.5 deg.

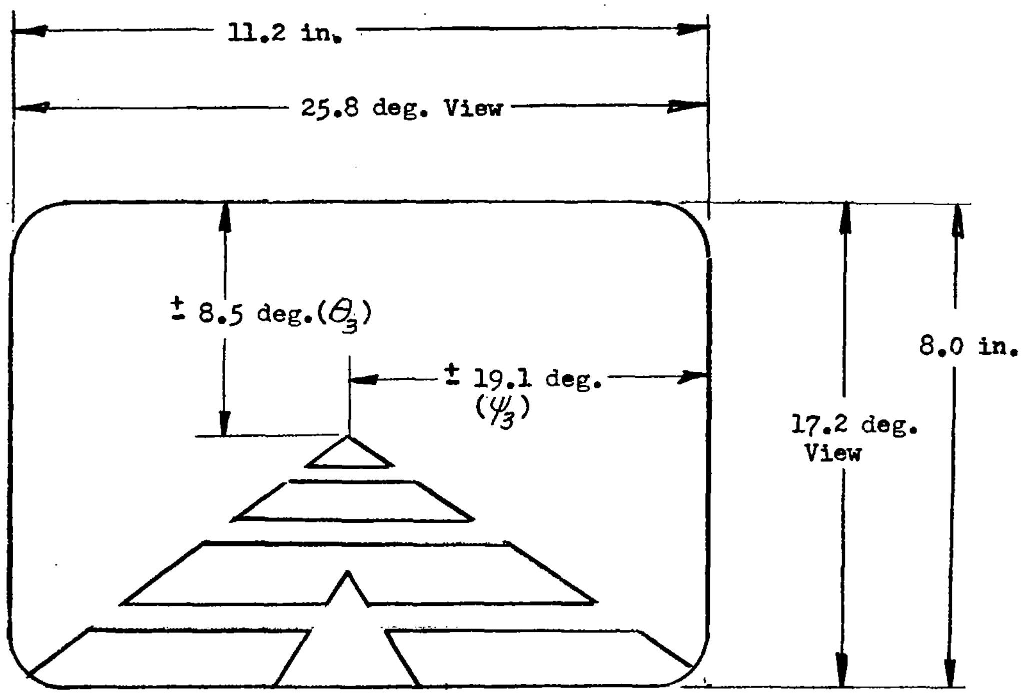
Full screen deflection of the starfield, horizon, and ground plane were produced with ψ_3 and θ_3 values ± 12.9 and ± 8.6 deg., respectively, in the ATTITUDE mode and with ψ_H and γ values of ± 3.2 and ± 4.3 deg., respectively, in the PATH mode. These values are illustrated in Figure II-A-1.

The lateral offset and altitude error drive signals were as defined by equations 115-117 of Appendix I-A with the maximum displayed error for each being ± 100,000 feet, i.e., errors greater than 100,000 feet produced no changes in path lateral offset of path width. Automatic scale change capabilities, as well as single scale, were incorporated for the ΔY_{DIS} and Δh_{DIS} signals. With the automatic scale changes, the ranges were provided for both ΔY_{DIS} and Δh_{DIS} - ± 10,000, ± 50,000, and ± 100,000 feet - the scale changes automatically performed at 10,000 and 50,000 feet.

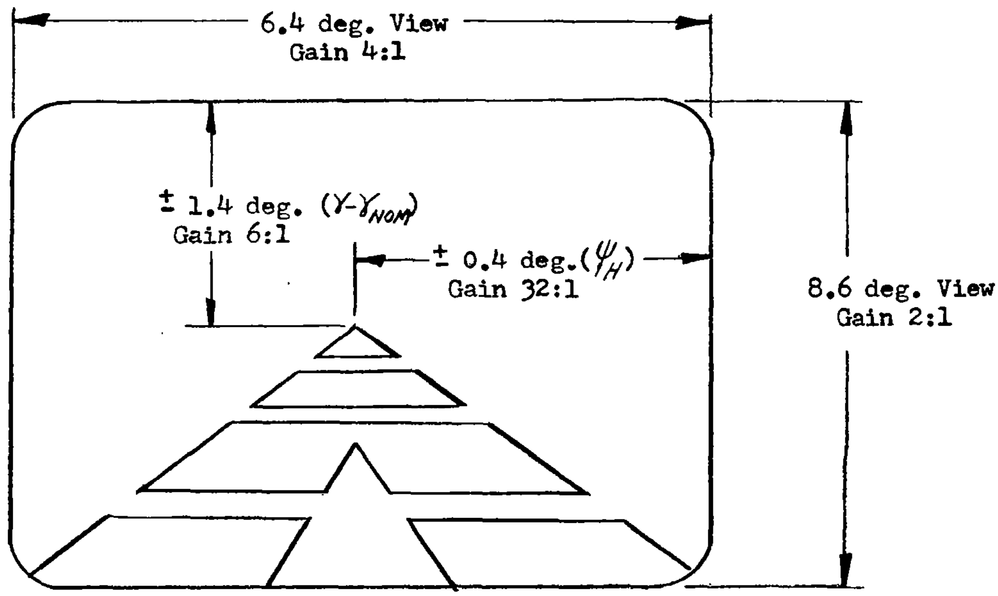
The tarstrips were used to denote the range of ΔY_{DIS} - the tarstrips on and moving as a function of velocity (normal operation) when the absolute error was equal to or less than 10,000 feet; the tarstrips on with a zero velocity input (tarstrips stationary) when the absolute error was greater than 10,000 feet but less than or equal to 50,000 feet; and the tarstrips turned off when the error was greater than 50,000 feet.

Path brightness was varied to denote Δh_{DIS} range - maximum with the error equal to or less than 10,000 feet; medium for 10,000 to 50,000 feet; and minimum for greater than 50,000 feet.

For single scale operation - ± 100,000 feet with no scale changes - the tarstrips were always on and moving and path brightness was always maximum.



SPACE VEHICLE ATTITUDE MODE



SPACE VEHICLE PATH MODE

FIGURE II-A-1 VERTICAL DISPLAY VIEW ANGLES AND GAIN VALUES

The K_{Ψ} logic was enabled for all runs in the Second Evaluation.

1.2 Horizontal Display

The horizontal display was the same as for the First Evaluation except that the horizontal situation display had only one display mode - the same as previously used with the COMMAND ATTITUDE mode with the required (command) flight path heading line and the digital readouts deleted.

2.0 DATA RECORDING PARAMETER COMPUTATION

The revisions to the printout data requirements for the Second Evaluation deleted the requirements for equations 97-101 of Appendix I-A. An additional equation was incorporated for h_{NOM}, nominal flight path altitude:

$$h_{NOM} = r_{NOM} - r_E \qquad (5)$$

The computations of the remaining data printouts were as defined in Appendix I-A.

3.0 COMPUTER DATA INPUTS

The data inputs for computer program during the Second Evaluation were the same as stated in Section 3.0 and revised by Section 4.0 of Appendix I-A.

APPENDIX II-B

RAW SCORE DATA BY SUBJECT
SECOND EVALUATION

SUBJECT FLIGHT NO.	INITIAL COND.	SCALES	FLIGHT PATH ERRORS ELEV. ϵ_γ DEG.	HEAD. ψ_H DEG.	VEL. ϵ_v FPS	POSITION ERRORS LATERAL Y_P FT	LONG. Z_P FT	ALT. Δh FT	CONTROL ENERGY EXPENDITURE PITCH %	YAW %	ROLL %
1	1	3	-1.486	1.658	-7,611	35,719	10,074	-40,056	40.52	16.53	18.48
2	8	3	-1.091	1.978	-3,692	34,738	8,663	-53,045	29.24	23.00	16.19
3	1	3	-2.553	.987	-354.8	7,053	11,139	2,194	24.61	12.45	10.75
4	2	3	-.320	-3.468	-6,601	-36,946	7,273	-8,193	21.11	30.08	23.08
5	1	3	-.054	-.057	-14.6	-3,478	411	4,113	10.56	5.27	5.01
6	14	3	-2.769	-2.088	-5,216	211,396	14,725	-7,851	37.52	15.91	14.87
7	1	3	-.679	-.231	5.7	-48	24,594	-35,977	19.25	8.89	16.64
8	12	1	-.295	-.509	-8.1	-30,559	1,624	1,802	12.09	11.97	8.28
9	1	1	-.196	-.027	-4.6	-4,127	889	5,455	13.34	6.05	4.73
10	6	1	-.173	.018	-12.1	-14,819	1,023	10,009	19.11	9.29	6.87
11	1	1	-.127	-.032	2.9	-3,627	690	-5,171	14.64	5.56	5.48
12	10	1	-.337	.082	1.9	-6,214	8,026	-73,931	32.17	14.88	10.67
13	1	1	-.577	.001	15.5	-6,874	2,075	-4,897	13.53	5.71	3.33
14	4	1	-.304	-.001	-7.9	-4,759	1,983	-22,902	19.16	5.94	5.55

+: Up, Above, Right
-: Down, Below, Left

INJECTION POINT CONDITIONS
SUMMARY

SUBJECT NO. 1

SUBJECT FLIGHT NO.	INITIAL COND.	SCALES	FLIGHT PATH ERRORS: ELEV. ϵ_r DEG.	FLIGHT PATH ERRORS: HEAD. ψ_H DEG.	FLIGHT PATH ERRORS: VEL. ϵ_V FPS	POSITION ERRORS: LATERAL Y_P FT	POSITION ERRORS: LONG. Z_P FT	POSITION ERRORS: ALT. Δh FT	CONTROL ENERGY EXPENDITURE: PITCH %	CONTROL ENERGY EXPENDITURE: YAW %	CONTROL ENERGY EXPENDITURE: ROLL %
1	1	1	-1.719	.136	-.50	1,769	8,554	-26,244	14.26	10.50	9.23
2	15	1	-1.499	.079	11.3	-43,188	6,896	-16,510	18.47	11.48	9.38
3	1	1	1.330	.001	-7.5	1,251	-2798	8,018	13.68	4.78	2.32
4	5	1	.094	.011	10.1	-17,455	22,371	-41,144	15.83	20.12	16.75
5	1	1	-.184	0.0	39.9	-669	1,147	34,826	8.33	5.88	1.42
6	3	1	-1.227	-.049	80.9	-5,495	10,099	27,801	15.76	12.99	11.17
7	1	1	.035	-.002	5.9	-3,739	1,527	22,901	10.53	6.31	5.77
8	7	3	-1.013	.008	21.7	-1,319	7,696	-15,151	21.42	10.51	13.14
9	1	3	-.168	.034	5.6	1,543	565	-13,912	16.07	7.53	6.86
10	1	3	-.813	-.214	639.7	-3,408	9,349	-12,272	27.09	17.05	21.63
11	13	3	-.993	-.017	-3.6	-1,234	6,374	-2,548	16.62	12.99	14.06
12	11	3	-.703	-.009	21.6	572	4,313	39,044	13.20	16.46	11.05
13	1	3	-.136	.024	13.3	1,075	2,341	4,622	19.91	4.91	3.28
14	9	3	-.504	.033	20.1	-176	4,998	3,804	22.72	12.18	12.47

INJECTION POINT CONDITIONS
SUMMARY

SUBJECT NO. 2

FLIGHT NO.	INITIAL COND.	SCALES	FLIGHT PATH ERRORS ELEV. ϵ_γ DEG.	HEAD. ψ_H DEG.	VEL. ϵ_v FPS	POSITION ERRORS LATERAL Y_p FT	LONG. Z_p FT	ALT. Δh FT	CONTROL ENERGY EXPENDITURE PITCH %	YAW %	ROLL %
1	1	3	-.307	-.004	-11.7	692	211	1,090	10.84	10.09	10.97
2	6	3	-.202	.072	-5.3	-2,519	1,850	4,046	22.47	15.18	15.79
3	1	3	.068	.017	-11.3	643	-274	2,585	12.79	9.83	8.24
4	4	3	.016	-.003	8.6	710	157	2,583	16.78	11.52	7.07
5	1	3	.072	.006	-4.8	356	-311	3,228	12.90	11.93	10.03
6	12	3	-.294	.006	4.9	305	2,242	4,454	18.79	18.75	20.10
7	1	3	-.107	.013	-6.4	300	474	2,557	12.06	10.16	10.43
8	2	1	-.428	.058	397.4	16,214	3,623	-186	22.59	3.42	10.98
9	1	1	-.307	-.011	1.2	1,573	1,686	-763	23.53	10.11	10.66
10	10	1	-.098	-.004	-1.5	-1,326	629	30,912	9.41	10.18	9.26
11	1	1	.053	.009	-5.2	792	-209	3,903	14.03	8.45	10.35
12	8	1	-.175	-.031	8.8	11,384	781	1,369	15.01	5.59	9.67
13	1	1	-.132	-.003	-4.3	2,151	767	-86	15.09	8.28	9.58
14	14	1	-.291	0.00	18.4	1,437	3,404	11,024	13.27	15.48	16.21

INJECTION POINT CONDITIONS
SUMMARY

SUBJECT NO. 3

SUBJECT FLIGHT NO.	INITIAL COND.	SCALES	FLIGHT PATH ERRORS			POSITION ERRORS			CONTROL ENERGY EXPENDITURE		
			ELEV. ϵ_γ DEG.	HEAD. ψ_H DEG.	VEL. ϵ_V FPS	LATERAL Y_P FT	LONG. Z_P FT	ALT. Δh FT	PITCH $	YAW $	ROLL $
1	1	1	-.388	.015	51.5	4,391	2,962	37,868	15.93	17.07	11.31
2	11	1	-.040	-.402	6.4	40,734	768	60,699	15.72	15.20	8.63
3	9	1	-2.246	-.010	-15.6	-41,518	12,669	-32,434	26.21	22.30	12.97
4	1	1	-.677	-.116	.44.7	5,247	5,557	-1,679	17.05	9.52	6.22
5	3	1	.308	.403	42.3	-32,007	1,157	10,970	N/A	N/A	N/A
6	1	1	.186	.034	-12.9	7,493	-651	24,285	13.41	14.16	4.39
7	13	1	-.128	-.009	-6.1	2,151	2,891	-6,655	29.16	9.24	5.69
8	1	3	-1.506	.126	33.5	862	14,624	51,025	11.83	25.64	14.73
9	5	3	.106	-.219	-8.6	10,019	-209	1,421	11.62	15.04	9.62
10	1	3	-1.017	-.337	83.2	-12,277	6,891	-11,622	22.76	16.56	12.24
11	7	3	.153	-.053	-2.8	314	-731	3,864	14.40	14.59	6.32
12	1	3	-.105	.042	-.013	1,065	2,217	3,970	17.79	11.85	9.09
13	15	3	-.422	.171	34.9	-27,413	3,503	-9,750	8.42	9.81	9.62
14	1	3	-.616	-.042	-11.3	-326	2,799	4,853	18.20	12.03	9.71

N/A - NOT AVAILABLE

INJECTION POINT CONDITIONS
SUMMARY

SUBJECT NO. 4

SUBJECT FLIGHT NO.	INITIAL COND.	SCALES	FLIGHT PATH ERRORS ELEV. ϵ_γ DEG.	HEAD. ψ_H DEG.	VEL. ϵ_v FPS	POSITION ERRORS LATERAL Y_p FT	LONG. Z_p FT	ALT. Δh FT	CONTROL ENERGY EXPENDITURE PITCH $	YAW $	ROLL $
1	5	1	-.645	.022	16.1	1,665	4,619	37,339	14.93	16.86	16.05
2	7	1	-.512	.004	619.4	9,604	5,649	-5,169	16.66	15.02	12.46
3	1	1	-.685	-.061	8.1	5,623	3,416	-1,874	17.90	20.84	17.70
4	15	1	-.939	-.427	30.4	-12,727	11,227	6,465	15.88	29.60	30.63
5	13	1	-.169	.026	-4.0	9,272	-566	5,049	10.14	8.58	7.62
6	1	1	.000	2.084	-17,124	37,889	12,079	118	N/A	N/A	N/A
7	1	1	-.278	.004	-5.3	-2,456	1,184	4,289	12.32	5.22	5.31
8	4	3	1.482	-1.004	-2,059	45,052	24,723	14,739	28.89	23.08	27.57
9	1	3	-.625	-.018	-414.3	-2,933	2,717	9,922	20.47	5.03	4.35
10	3	3	-1.105	.046	19.5	-37,153	5,359	20,048	13.07	9.30	8.23
11	1	3	-.705	-.034	-2.8	357	3,719	8,789	17.49	4.95	4.72
12	1	3	-.223	-.016	-13.7	-382	974	5,962	15.22	4.98	5.24
13	11	3	-2.317	-.835	-2,706	38,968	23,985	-69,641	16.81	25.99	20.02
14	1	3	-.192	-.001	-0.3	-1,813	2,645	-1,278	20.17	10.54	6.85

INJECTION POINT CONDITIONS
SUMMARY

SUBJECT NO. 5

SUBJECT	FLIGHT NO.	INITIAL COND.	SCALES	FLIGHT PATH ERRORS			POSITION ERRORS			CONTROL ENERGY EXPENDITURE		
				ELEV. ϵ_γ DEG.	HEAD. ψ_H DEG.	VEL. ϵ_V FPS	LATERAL Y_P FT	LONG. Z_P FT	ALT. Δh FT	PITCH $	YAW $	ROLL $
	1	4	3	-.259	.014	-5.1	969	1,703	423	21.46	17.99	6.60
	2	1	3	-.177	.031	12.5	305	822	3	9.46	11.56	4.40
	3	6	3	-1.305	-1.116	-45.6	-18,689	17,261	-34,882	19.98	18.64	9.66
	4	1	3	-1.234	-.165	-174.9	-1,351	6,488	-634	19.09	13.65	6.61
	5	14	3	-.601	-.358	11.7	706	13,427	26,898	24.21	19.14	13.79
	6	1	3	-.754	-.164	18.6	-989	5,728	-2,369	27.08	18.99	10.16
	7	10	3	-.411	-.036	8.3	220	2,571	-1,103	12.54	10.58	1.77
	8	1	1	-.141	-.006	2.3	2,962	623	1,834	11.51	6.28	1.42
	9	8	1	-.246	.006	4.0	-3,016	1,889	13,955	24.59	18.08	11.76
	10	1	1	-.033	.009	-12.9	280	181	7,171	8.08	6.99	1.75
	11	2	1	-.698	-.125	13.2	-1,149	6,711	3,529	19.46	19.69	13.09
	12	1	1	.076	-.012	-7.2	-1,779	-239	11,903	9.25	8.53	2.93
	13	1	1	-.221	-.009	13.7	1,273	1,178	718	17.72	19.27	8.50
	14	12	1	-2.465	.133	15.2	948	8,246	86,816	14.69	26.41	9.17

INJECTION POINT CONDITIONS
SUMMARY

SUBJECT NO. 6

APPENDIX II-C

PILOT QUESTIONNAIRE
SECOND EVALUATION

NASA DISPLAY/CONTROL STUDY
SECOND EVALUATION
PILOT REPORT

1. VERTICAL DISPLAY

1A - In the Thrust Phase did you find that following the nominal flight path, rather than attitude commands, made the task of cisplanetary injection ...

RATING SCALE	GROUP (MEAN)	INDIVIDUAL			
(1) more difficult	(1.0)	1.	(1)	4.	(?)
(2) no difference		2.	(1)	5.	(1)
(3) easier		3.	(1)	6.	(1)
(1) less interesting	(2.4)	1.	(2)	4.	(?)
(2) no difference		2.	(1)	5.	(3)
(3) more interesting		3.	(3)	6.	(3)

1B - Did the absence of vehicle attitude information handicap you in achieving the nominal flight path?

(1) considerably	(1.6)	1.	(1)	4.	(?)
(2) occasionally		2.	(1)	5.	(1)
(3) not at all		3.	(2)	6.	(3)

1C - Was the Vertical Display, in the Thrust Phase, more realistic than in the first evaluation?

(1) less realistic	(2.0)	1.	(1)	4.	(2)
(2) no difference		2.	(-)	5.	(2)
(3) more realistic		3.	(3)	6.	(2)

1D - During the Thrust Phase, when estimating your heading and elevation angles, estimate the per cent of time you relied upon (1) direction and extent of displacement of tip of path from cross; (2) vehicle flight path attitude as given by horizon, ground scene, and sky field movement.

(1) ____%	(1) 79%*	1.	(1 - 80%)	4.	(1 - 75%)
	(2) 36%*		(2 - 20%)		(2 - 25%)
(2) ____%		2.	(1 - 40%)	5.	(1 - 90%)
			(2 - 50%)		(2 - 10%)
		3.	(1 - 100%)	6.	(1 - 80%)
			(2 - 90%)		(2 - 20%)

* Percentages do not total 100% because two subjects gave percentages totaling more or less than 100%.

1E - Did the lag in nominal flight path movement following attitude controller input result in any confusion?

(1) considerably	(1.5)	1.	(1)	4.	(1)
(2) occasionally		2.	(1)	5.	(1)
(3) not at all		3.	(3)	6.	(2)

1F - Rate the velocity marker as a cue for thrust initiation and cutoff.

(1) poor	(2.5)	1.	(3)	4.	(2)
(2) fair		2.	(2)	5.	(3)
(3) good		3.	(2)	6.	(3)

2. HORIZONTAL DISPLAY

2A - Did you use the Horizontal Display more or less often in this evaluation than in the First Evaluation?

RATING SCALE	GROUP (MEAN)	INDIVIDUAL			
(1) less often	(3.0)	1.	(3)	4.	(3)
(2) no difference		2.	N/A	5.	(3)
(3) more often		3.	(3)	6.	(3)

2B - Did you use information on the Horizontal Display to supplement that on the Vertical Display?

(1) not at all	(2.8)	1.	(3)	4.	(3)
(2) some		2.	(2)	5.	(3)
(3) often		3.	(3)	6.	(3)

If (2) or (3) define information used

a. Vehicle position with respect to nominal path
b. Vehicle path heading
c. Vehicle position with respect to thrust initiation line
d. Vehicle position with respect to thrust termination

a. 83%	1. (a,b,c,d)	4. (a,b,c,d)
b. 100%	2. (b)	5. (a,b,c)
c. 83%	3. (a,b,c)	6. (a,b,c,d)
d. 50%		

3. IF YOU HAD DIGITAL INFORMATION IN THE FIRST EVALUATION, DID THE ABSENCE OF THIS NUMERICAL INFORMATION HANDICAP YOU IN THIS EVALUATION?

(1) found tasks more difficult without it	1.	N/A	4.	(3)
(2) would like it on certain maneuvers	2.	N/A	5.	N/A
(3) not at all	3.	(2)	6.	(2)

(2.3)

4. SYSTEMS MONITORING

4A - Was the systems monitoring task during the Thrust Phase more or less distracting than in the First Evaluation?

(1) more distracting	(2.6)	1.	(3)	4.	(2)
(2) no difference		2.	N/A	5.	(3)
(3) less distracting		3.	(2)	6.	(3)

4B - How important did you consider the systems monitoring task? Indicate by apportioning your time in percentages between the two tasks as you recall it.

RATING SCALE		GROUP MEANS	INDIVIDUAL (in %) 1	2	3	4	5	6
During coast:	Flight management (%)	(59%)	20	50	60	80	95	50
	Systems monitoring(%)	(41%)	80	50	40	20	5	50
During thrust:	Flight management (%)	(76%)	50	50	90	90	95	80
	Systems monitoring(%)	(24%)	50	50	10	10	5	20

5. SCALE CHANGING

5A - Did you find that the scale changing during thrust provided a more sensitive feedback on your achievment of nominal flight path?

(1) Was more detrimental than a single scale (2) No difference from use of a single scale (3) Assisted in acquisition of the nominal path	(1.8)	1. (1) 2. (2) 3. (3)	4. (1) 5. (1) 6. (3)

5B - Would you recommend a different combination of scale changing?

(1) No (2) Yes (Explain)*	1. (1) 2. (2) 3. (2)	4. (1) 5. (2) 6. (1)

* See Section 3.6.4.5 for recommendations.

5C - Which cues are most helpful as an index (indices) of scale changing?

	GROUP MODE		
(1) tar strip presence and motion (2) brightness changes (3) shift in flight path	(2)	1. (1) 2. (2) 3. (3)	4. (3) 5. (2) 6. (2)

6. GENERAL PANEL LAYOUT

6A - From a pilot's standpoint, what struck you as particularly good about the panel layout?

1. The relocation of the task loading (CLEAR) button to the left side panel from the right hand panel in the First Evaluation. This change permitted the right hand to be kept continuously on the controller during thrust.

2. Ease of access to all controls.

3. The tandem arrangement of the Horizontal and Vertical Displays.

4. The initial training received on the Attitude Mode Displays.

6B - What struck you as especially objectionable about the panel layout?

1. The Horizontal Display was too small and outlines were somewhat blurred.
2. The moving index on the Horizontal Display was not displaced far enough from the nominal path.
3. Inability to read panel light labeling until they were lit.
4. The scan angle between the Horizontal and Vertical Displays was too great.

6C - Rate the panel layout.

	GROUP MEAN	INDIVIDUAL			
(1) poor	(2.3)	1.	(3)	4.	(2)
(2) satisfactory		2.	(2)	5.	(3)
(3) good		3.	(2)	6.	(2)

7. ANY ADDITIONAL COMMENTS OR CRITICISMS OF THE SIMULATION OR ANY PANEL FEATURES.

Comments are discussed under Section 3.6.4, Questionnaire Analysis.