P64-22

GPO PRICE $ ____

CFSTI PRICE(S) $ ____

Hard copy (HC) 3.00

Microfiche (MF) .50

ff 653 July 65

MANUAL ATTITUDE CONTROL SYSTEMS:

VOLUME II. DISPLAY FORMAT CONSIDERATIONS

March 1964

FACILITY FORM 602

N66-12856 (ACCESSION NUMBER)	(THRU)
53 (PAGES)	/ (CODE)
CR-68192 (NASA CR OR TMX OR AD NUMBER)	11 (CATEGORY)

AEROSPACE GROUP

HUGHES

DISPLAY SYSTEMS DEPARTMENT
HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

MANUAL ATTITUDE CONTROL SYSTEMS:

VOLUME II. DISPLAY FORMAT CONSIDERATIONS

by
R. O. Besco

Prepared under Contract No. NASw-620 by

AEROSPACE GROUP
RESEARCH AND DEVELOPMENT DIVISION
HUGHES AIRCRAFT COMPANY
Culver City, California

for
National Aeronautics and Space Administration

FOREWORD

This study was sponsored by the National Aeronautics and Space Administration under Contract NASw-620, "Study of Flight Display and Control Integration for Manned Space Flight." The contract monitor was Major Leroy D. Paige, Chief, Crew Stations and Maintainability Factors, Office of Manned Space Flight. The work reported herein was accomplished between September 17, 1963 and January 20, 1964.

Several personnel of the Display Systems Department, Hughes Aircraft Company made major contributions to this phase of the study. Connie J. Goddard made contributions in experimental design, data collection and reduction and in writing the simulation and experimental sections. Carolyn S. McElwain collected the data and wrote the section entitled, Display Deflection Thresholds. Gene G. Depolo was responsible for the off-axis telescope studies. Hal M. Meyers and Gene G. Depolo provided engineering support both in terms of problem definition and mechanization of the simulation equipment. Jerry J. Leeson was responsible for operation and maintenance of the simulation. The Program Manager for Hughes Aircraft was D. K. Bauerschmidt, who provided considerable assistance along with Dr. S. N. Roscoe on report preparation and interpretation of results. Joe B. Setto and K. K. Klatt designed the locally fabricated display devices as well as the basic cockpit.

Special appreciation is due to Dr. Charles Kelley, Peter Strudwick and Meredith Mitchell of Dunlap and Associates for their assistance with the predictor display. Dick Winner of Hughes designed the symbol generator used for the predictor display. Larry Day, Jeff Glassman, Ed Hoffman, Bill Kitz, Bob Nall, Verdi Pieroni, Bob Norris and Chris Smith served as pilot-subjects.

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MANUAL ATTITUDE CONTROL SYSTEMS:

VOLUME II. DISPLAY FORMAT CONSIDERATIONS

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SUMMARY

Experimental simulation studies were conducted to investigate various display parameters and to compare four different formats for the display of spacecraft attitude information. Representative attitude control maneuvers were performed by experienced pilots in a fixed-base spacecraft simulator with kinematic computations performed by an analog computer. Definitions of various display formats and selected attitude display parameters are given.

The results of the studies are presented along with suggestions for attitude display design and implications for the selection of display formats.

author

INTRODUCTION

This volume contains the results of the second phase of a four-phase experimental program concerning manual attitude control of space vehicles. The goal of this program is to provide experimentally derived estimates of manual attitude control system performance over a broad range of values for major control system parameters. These data should provide design criteria for the development of system configurations and components which will improve the efficiency, accuracy, ease and safety of manual vehicle control.

During the first phase of the program the effects of the mode of system operation, e.g., direct manual, rate command, pulse, etc., upon system performance were investigated. Analytic and experimental investigations of operating modes were conducted to (1) define parameters critical to system performance, (2) find optimum values of these parameters and (3) provide comparative performance data among the various control modes. The results of the first phase were reported in Volume I (Besco, Depolo and Bauerschmidt, 1964).

In the phase just completed, the effects of selected attitude display techniques and parameters upon system performance have been investigated. In the third phase, the effects of controller parameters will be studied and in the fourth phase, the interactions of system modes, displays and controllers will be investigated. The report containing the results of the fourth phase (Volume IV) will also contain a summary of the results of the entire program.

The study approach employed during the phase just completed was similar to that described in Volume I. First, current and prospective methods of vehicle orientation and rotational rate presentation were reviewed. Several representative types of displays were chosen for study, including that used in the Mercury capsule and those planned for use in the Apollo and LEM spacecraft. An experimental program was conducted to optimize the selected display configurations and to obtain comparative system performance data using each of the configurations. Experienced pilots executed various attitude control maneuvers in a fixed base, simulated spacecraft with the kinematic computations, control system representation, display inputs and performance measurement provided by a general-purpose analog computer.

The major sections of this volume are: Problem Definition, containing a discussion of attitude display considerations; Simulation, containing a description of the simulation equipment; Exploratory Studies, containing the results of preliminary and exploratory studies; Experimental Studies, containing the description and results of the two main experiments; and Discussion, containing conclusions and recommendations of this phase of study.

PROBLEM DEFINITION

A generalized single-axis manual attitude control system block diagram is shown in Figure 1. This diagram illustrates the individual components of the system and can be used to define the particular components of the system being employed during this current phase of study. The first phase of study was concerned with the elements of the control system contained within the dashed rectangle. The elements contained within the double dashed rectangle have been studied during this current phase.

System Definitions

Each of the elements pictured in Figure 1 relates directly to a physical component. The astronaut observes spacecraft orientation, angular rates and possibly angular accelerations, and exercises control over the spacecraft attitude through his hand controller. The hand controller transforms an astronaut's hand, wrist or finger movements into the appropriate electrical signals or mechanical movements to initiate the operation of actuators or to act as command signals against which actuators may be made to operate. The operation of the actuation devices causes angular acceleration of the spacecraft which is in turn sensed by the sensor elements. The sensed orientation and rate are then processed and displayed to the astronaut.

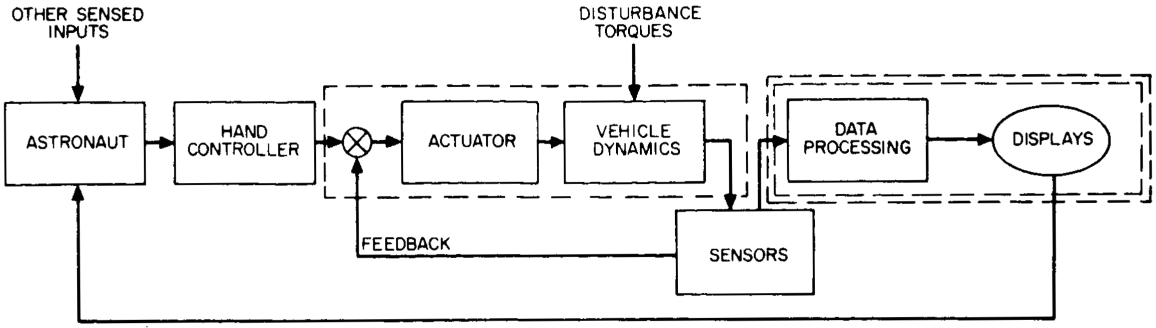

Figure 1. Attitude Control System Block Diagram

After the spacecraft orientation angles and body rates have been sensed the signals may be modified before being displayed. The signal processing element of the manual control system modifies these sensed angle and rate signals. The nature of the modification will be determined by the nature of the display configuration and by the task to be performed by the astronaut. The modification may include scale factoring, quickening, predicting, etc. Emphasis in this study has been placed upon the evaluation of the display scale factor, and comparison of particular display formats available to the astronaut during performance of various attitude control tasks.

The displayed information required by an astronaut for manual control of spacecraft orientation is similar to that required for control of a high performance aircraft. However, the extension of aerodynamic flight to oribital flight has been made necessary the modification of typical aircraft orientation displays. Where aerodynamic vehicles are relatively stable about the major axes, orbital vehicles are neutrally stable with no natural damping. The majority of aircraft control is performed about the pitch and roll axes while spacecraft control must have involve the pitch, roll and yaw axes.

As a result of these major differences, displays for manual control of spacecraft orientation must present vehicle orientation about three axes rather than about two axes. They must allow the presentation of vehicle attitude in all orientations relative to the reference axes rather than a limited range of orientations relative to the reference axes. Since the spacecraft contains no natural damping, additional information necessary for stable vehicular control is required (See Lear, 1963, Bauerschmidt and Besco, 1962 and Ritchie, Hanes and Hainsworth, 1960). This information includes as a minimum pitch, roll and yaw body rates but may include signals containing derivative information.

For the purposes of this phase of study, the sensor has been assumed to supply roll, pitch and yaw angles to define continuously the orientation of the spacecraft as well as roll, pitch and yaw body rates. As in the first phase, roll angle has been defined as the angle formed by the lateral axis of the vehicle and the horizontal reference plane in a plane normal to the longitudinal axis of the vehicle. It is measured from zero through positive and negative angles to a common 180-degree point.

Pitch angle has been defined as the angle formed by the longitudinal axis of the vehicle and the horizontal reference plane measured in a plane normal to the horizontal reference plane. Pitch angle is measured from zero, where the longitudinal axis of the vehicle is located within the horizontal reference plane, to the positive 90 degree point and to the negative 90 degree point.

Yaw angle has been defined as the angle in the horizontal reference plane formed by the normal projections of the velocity vector and the vehicle longitudinal axis onto the horizontal reference plane. Yaw angle is measured from zero through positive and negative angles to a common 180-degree point.

A basic point of departure in these studies has been that the information presented by attitude displays should include individual presentations of angular orientation and rate quantities. Implicit in this statement is that the astronaut has the capability to interpret his attitude presentation and control the spacecraft without the aid of computed command signals.

To be certain, aids such as vernier error indicators, attitude profile computations, autopilots, and rate feedback control systems will greatly reduce the burden on the astronaut. The point is that the displays should include the orientation and body rate information directly so that the astronaut may remain in complete command over the orientation, choice of rotational sequences and magnitude of body rates of the spacecraft.

Display Descriptions

Four types of attitude display formats were selected for this study. Each presents attitude angle and body rate information independently at approximately equivalent scale factors. None of the displays contained any flight-director type of indication.

The four types of attitude formats selected for study are described below. Figure 2 contains illustrations of each display format as it would appear for selected attitudes of the vehicle.

Three-Axis Attitude Ball Display. The three-axis attitude ball display was a Lear Model 4060C which is typical of the attitude displays found in high-performance aircraft. In addition, it is similar to that planned for use in the Gemini and Apollo spacecraft.

This display, shown in Figures 3 and 4, provides an integrated, "inside-out" presentation of vehicle attitude. Vehicle attitude is shown by the orientation of the sphere located inside the instrument relative to an aircraft-type symbol fixed to the display cover glass. As the vehicle rotates the sphere remains aligned with a set of reference axes as sensed by an inertial reference located within the vehicle. In effect, the vehicle rotates about the sphere which is fixed in inertial space. The display and control relationships require the astronaut to "fly" the fixed symbol toward the desired attitude on the sphere. This follows the so-called "fly-to" principle.

If, for example, the spacecraft is pitched down, the horizon (the division between light and dark hemispheres) will appear above the fixed vehicle symbol. If the astronaut desires to align his spacecraft with the reference axes, i.e., zero pitch, yaw and roll angles, he must establish a pitch-up body rate and "fly-to" the desired attitude. When this rate is established, the spacecraft will rotate about the sphere, and the "horizon" will move toward the fixed vehicle symbol. As the horizon reaches the fixed symbol, the pitch-up body rate is nulled to bring the vehicle to rest at the desired attitude.

Since the sphere rotates in an analogous one-to-one fashion with the outside field of view as seen through the spacecraft window, the sphere cannot directly be used at an increased scale factor which may be required for more precise spacecraft orientation. For this reason the cross-pointer indices overlaying the sphere have been mechanized to present vernier pitch and yaw attitude angles relative to zero pitch and yaw angles. Vernier roll attitude angle was presented on the conventional rate of a turn needle. The scale factor for this presentation was studied during this program as will be described in a later section.

The three-axis attitude ball presentation has been suggested for use in spacecraft for two major reasons. Firstly, the motion relationships of the display and of the external field of view are consistent so that a single set of logical control rules can be applied for situation of spacecraft control using either an instrument reference or an external field-of-view reference. Secondly, this presentation capitalizes on the prior training and experience of astronaut/test pilots in that it is similar to high-performance aircraft attitude presentations. In addition, mechanization of this type of display has evolved over many generations of aircraft to result in devices with relatively high operating reliability.

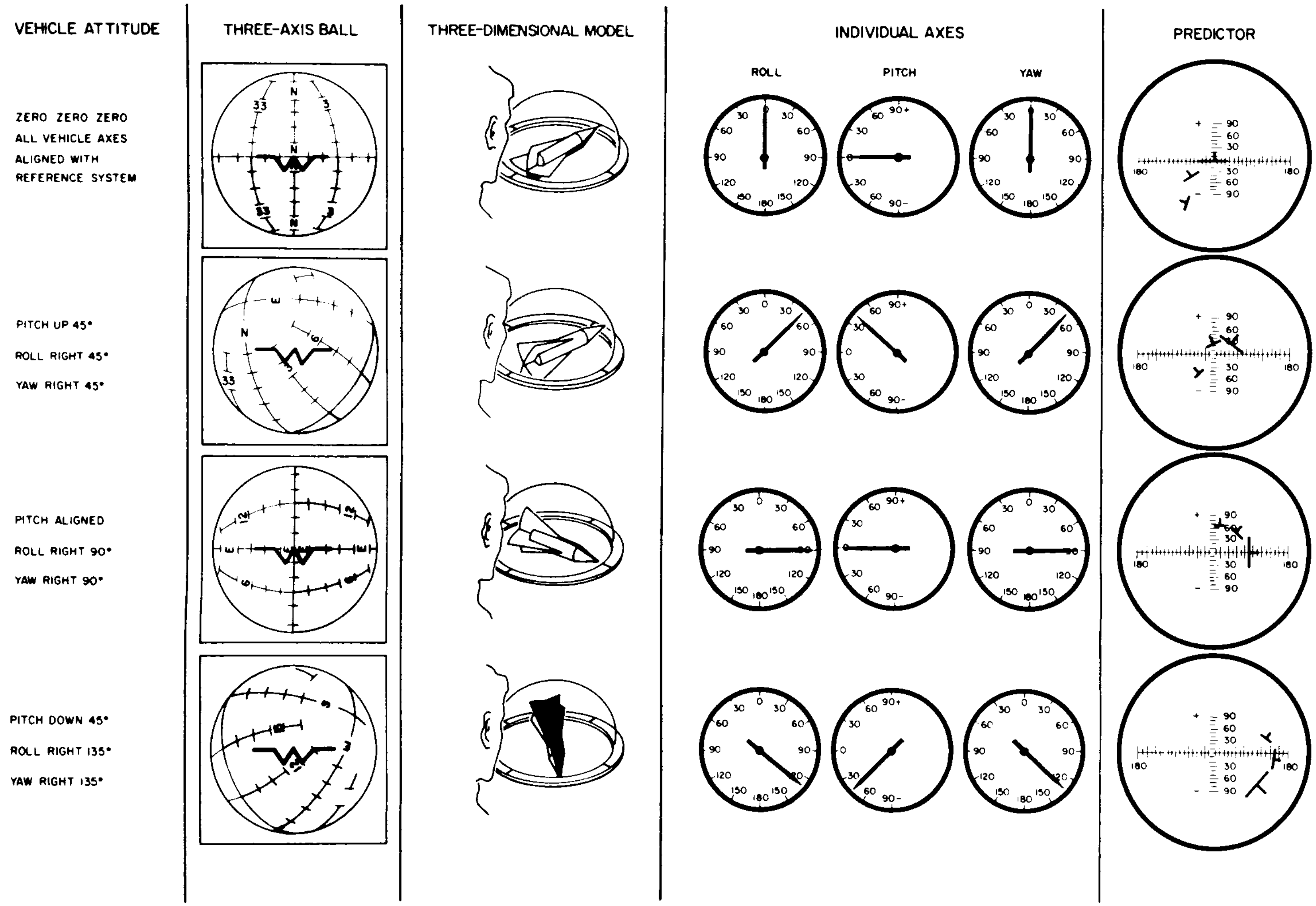

Figure 2. Attitude Presentations of the Display Types

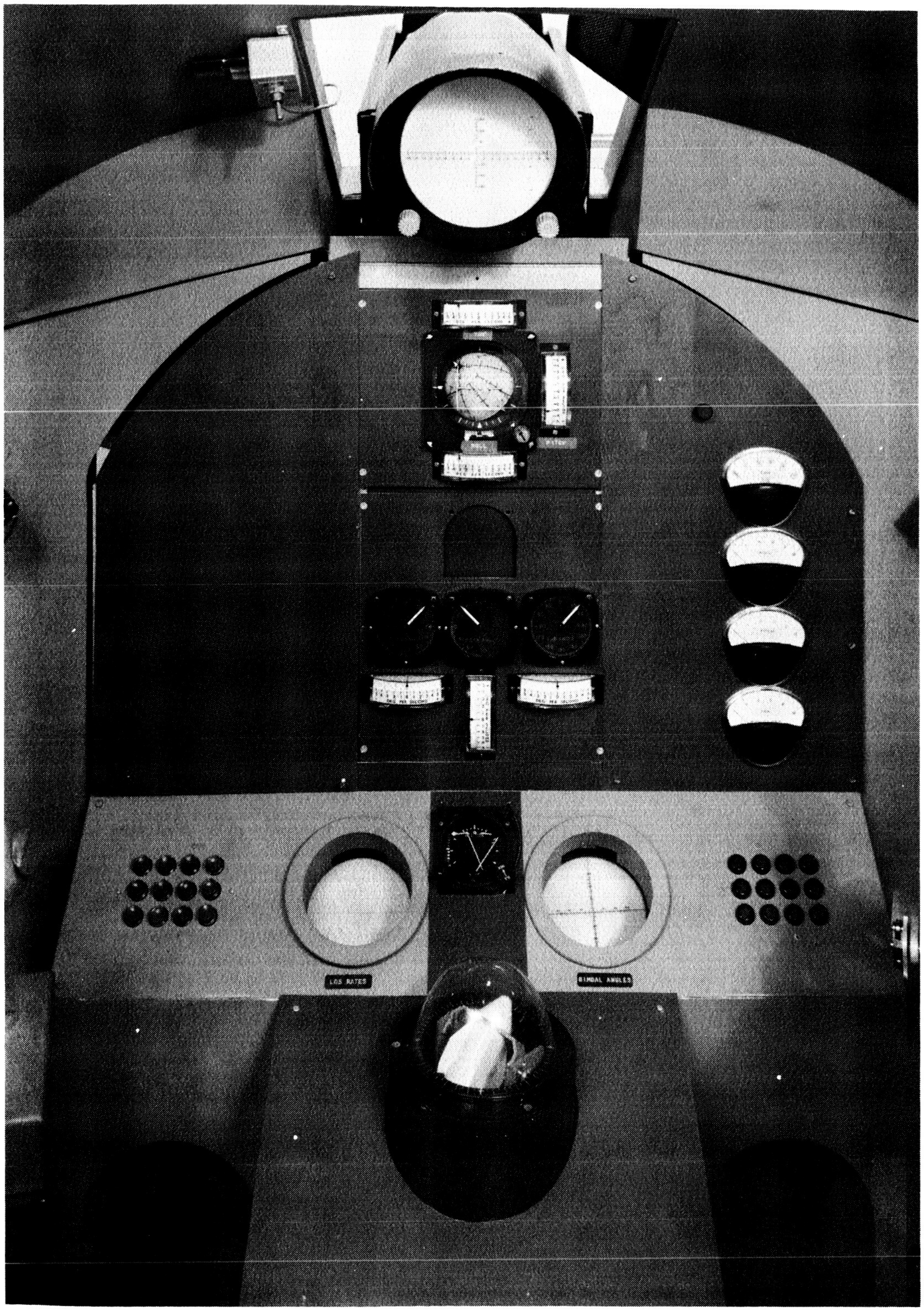

Figure 3. Simulator Display Console

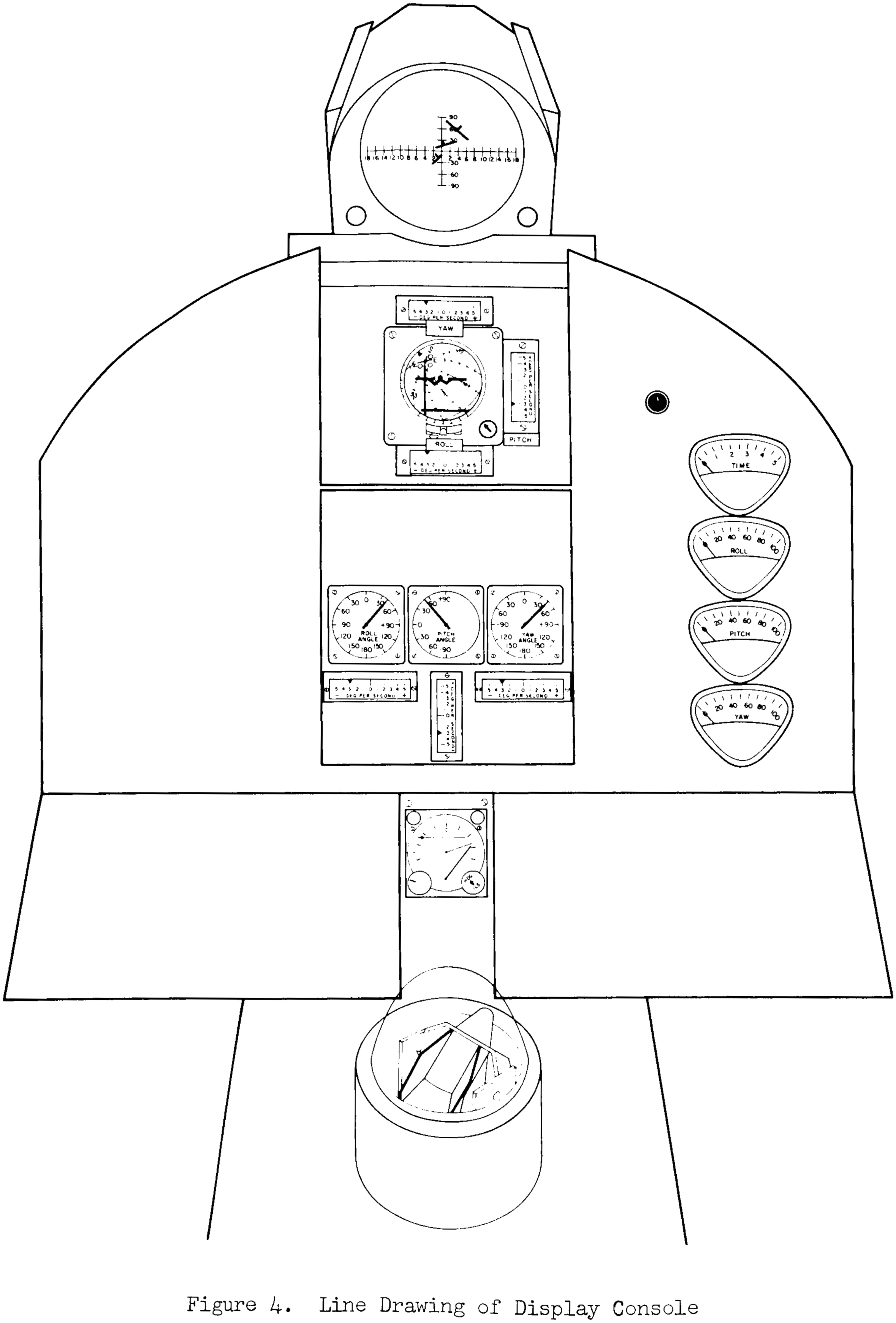

Figure 4. Line Drawing of Display Console

Three-dimensional model display. A three-dimensional spacecraft model which illustrates the direct analog display concept was also used in these experimental studies. This display concept refers to the utilization of a model as the primary display element. This model moves in an analogous fashion to the controlled element or spacecraft.

The application of this concept to spacecraft attitude display has been discussed for several years. A display employing a three-dimensional model of a spacecraft was described in Hopkins, Bauerschmidt and Anderson, 1960. The model was capable of unrestricted motion about all three model axes and could be viewed through a transparent hemisphere. This display was shown in mockup form; no operational version was mechanized. Other displays similar to that described above have been reported and shown in mockup form (Hopkins, Bauerschmidt and Roscoe, 1961, and Bauerschmidt and Besco, 1962).

The particular display mechanization studied in this program was designed and fabricated at Hughes Aircraft Company in early 1963 for use in simulation programs of this type. The device incorporated a model of a typical spacecraft, with fins and color coding to make attitude easily determined. The spacecraft model was mounted in a three-gimbal suspension system and was capable of continuous and simultaneous rotation about all three axes.

The model display was located below the main display panel as shown in Figures 3 and 4. The horizontal mounting plane of the model display and the forward direction of the spacecraft cabin defined the spacecraft attitude reference system. The model orientation relative to this system presented in analog form the spacecraft roll, pitch and yaw angles. For example, if an earth or lunar orbit situation were to be represented, the horizontal mounting plane would represent the local horizontal, and the forward cabin direction the spacecraft's velocity vector. In a transearth or translunar trajectory the horizontal would represent an arbitrarily selected stellar reference plane. Thus, when a subject was seated in the simulator cabin the orientation of the three-dimensional model relative to its mounting and forward reference indices corresponded to the orientation of the simulated spacecraft relative to its attitude reference axes.

Individual axes display. This display of spacecraft orientation was composed of three individual instruments reading the Euler angles about each of the three axes. The attitude display used in the Mercury capsule was very similar in concept to this display. The three individual instruments provide a light weight and reliable presentation with low power consumption. They provide separate, quantitative readouts of attitude angles.

Predictor display. The predictor display concept, developed by Kelley (1960), utilizes present position and rates of movement to predict position at selected future times. Kelley (1962) and Fargel and Ulbrich (1963) have provided excellent descriptions of the predictor and its operational advantages.

The predictor principle has been extensively studied for presenting vehicular position relative to linear reference systems. It was desired in this study to investigate the possibilities of utilizing the predictor principle to present vehicle attitudes or vehicular orientation to an angular reference system.

The predictor principle could be used with a number of different formats. In this study the angular reference system was displayed as a flat surface on a cathode-ray tube. Vehicle drone symbols of progressively smaller size represented the spacecraft's attitudes at future times.

One of the major advantages of the predictor display is that all the information necessary for attitude control is integral to the display. Vernier attitude indications are accomplished by a scale factor change available to the pilot whenever the spacecraft's pitch and yaw axes are close to their respective reference axes. The rates of movement about each of the three axes can be extrapolated by the pilot by comparing present attitude to future attitude.

SIMULATION

The Hughes Manned Space Flight Simulation Facility, as described in Volume I, was used in this study for the simulation of control system characteristics, for the computation of kinematic relationships, for the generation of displays in the crew station, and for the recording and processing of experimental data.

Computer

The analog computer was mechanized to (1) solve the vehicle equations of motion, (2) compute coordinate transformations, (3) simulate control system and actuator characteristics, (4) compute performance measures, (5) simulate disturbance torque signals, and (6) provide computer-control logic.

Equations. The computer performed the real time solution of the following equations:

$$\dot{p} = \left[\frac{L + (I_{yy} - I_{zz})qr}{I_{xx}}\right] + \dot{p}_c \qquad (1)$$

$$\dot{q} = \left[\frac{M + (I_{zz} - I_{xx})pr}{I_{yy}}\right] + \dot{q}_c \qquad (2)$$

$$\dot{r} = \left[\frac{N + (I_{xx} - I_{yy})pq}{I_{zz}}\right] + \dot{r}_c \qquad (3)$$

$$\dot{\phi} = p + \dot{\psi} \sin \theta \qquad (4)$$

$$\dot{\theta} = q \cos \phi - r \sin \phi \qquad (5)$$

$$\dot{\psi} = (q \sin \phi + r \cos \phi)\left(\frac{1}{\cos \theta}\right) \qquad (6)$$

Equations (1), (2) and (3) are the body rate/cross-coupling equations describing the dynamics of the angular motion of the spacecraft. Equations (4), (5) and (6) provided for the coordinate system transformation from body-referenced angles and rates to space-referenced Euler angles and rates. Derivations of these equations may be found in Goldstein (1953), Rauscher (1953) and Vermont (1962).

Disturbance torque generation. Five sine waves comprising the disturbance torque signals were generated by the computer. The frequencies of the five sine waves ranged from 0.019 cycles per second to 0.200 cycles per second. The amplitude and frequency components of the sine waves were summarized in Table 2, Volume I. The sine waves were summed and the output of the summer adjusted to yield an rms value of 0.154 degree/sec^2. A 90-second segment of the disturbance torque signal was recorded on magnetic tape and utilized as the forcing function during the tracking maneuver trials.

Computer control logic. An error-sensing circuit provided automatic hold of the computer when pre-specified terminal angle, body rate and time conditions were attained. The computer was placed in a hold condition automatically at the end of 105 seconds for the tracking tasks. For the stabilization, rate-nulling and attitude change maneuvers the computer was placed in hold automatically when the absolute values of all Euler angles were equal to or less than one degree and the absolute values of all vehicle body rates were equal to or less than 0.1 degree/sec.

Performance measurement. The computer calculated the mean-square angular error and the fuel consumed during each trial. At the end of each trial, records were made of these quantities as well as the time required for the trial.

Control modes. The three control modes used for this phase of the program were (1) the single-pulse mode, (2) the repeated-pulse mode and (3) the on-off acceleration mode.

In the single-pulse mode a pulse of specified shape and duration was applied by the pilot through control devices. The effect of this pulse was to impart an incremental change in angular rate to the vehicle. The pulse width was 50 milliseconds with 0.087 degree/sec rate increment per pulse. The repeated-pulse mode was similar to the single-pulse mode except a series of pulses was elicited by the astronaut's control device. The rate increment per pulse width was 0.087 with an average acceleration capability of 1.23 degrees/sec. In the on-off acceleration mode the effect of hand controller displacement was to command one specific angular acceleration for any hand controller displacement greater than some specified threshold, and zero acceleration for any displacement within the threshold. These were mechanized on the computer as shown in Appendix I, Volume I.

Crew Station

The crew station includes (1) attitude displays, (2) time remaining and fuel consumption readouts, (3) a hold indicator and (4) a manual controller.

In order to study a number of different display systems, the crew station configuration employed during the first phase of this program was rearranged and equipment added as shown in Figures 3 and 4. The most salient changes were: (1) the addition of a three-axis attitude ball display; (2) the addition of a three-dimensional model display; (3) the regrouping of the vernier attitude angle indicators and rate meters; and (4) the replacement of the cathode-ray tube attitude angle displays with more precise mechanical displays. In addition to the changes on the face of the display console, an oscilloscope was placed directly above the display console with the scope face oriented perpendicular to the subject's line-of-sight. This oscilloscope was used to present the predictor display.

Three-axis attitude ball display. The three-axis ball display, pictured in the center of Figures 3 and 4 was a Lear Siegler Model 4060C All-Attitude Indicator which employed a four-inch diameter reference sphere. Simultaneous and continuous rotations about all three axes were possible. The horizontal bar, vertical bar and turn needle were mechanized to present vernier information in pitch, yaw and roll, respectively. During one of the studies conducted in this phase of the program the scale factor of these vernier indicators was altered, with full scale representing pitch, roll and yaw angles between 0.5 and 10 degrees.

Three separate meters described below were used in conjunction with the three-axis ball to provide rate information. These meters were grouped about the ball as shown in Figures 3 and 4.

Three-dimensional model display. The three-dimensional model display used in these experiments was located below the main display panel in Figures 3 and 4. The spacecraft model was three and one-half inches in length, and its quadrants were color coded to assist in the interpretation of vehicle attitude. The spacecraft model was mounted in a three-gimbal suspension system allowing complete 360° rotation in pitch, yaw and roll. The outer gimbal contained the model yaw axis, the middle gimbal contained the pitch axis and the inner gimbal, the roll axis. The model was driven in yaw and pitch by servo motors and in roll by an internally mounted synchro resolver. A separate pointer and scale markings were provided around the yaw axis. The zero yaw angle index mark indicating the projection of the spacecraft's velocity vector in the horizontal plane was oriented toward the front simulator cabin.

Vernier attitude information was supplied by the Collins ILS instrument described below. A set of three rate meters located on the lower half of the panel were used in conjunction with the display.

Individual axes display. The individual axes display, as shown in Figures 3 and 4, consisted of three separate instruments displaying the spacecraft's attitudes about its three axes. From left to right, the instruments represented roll, pitch and yaw angles, respectively. Each instrument was three inches in diameter with one degree increments engraved on the dial faces. The readouts were identical to the three oscilloscope displays described in Volume I, except they were mechanical devices with scribed, lighted faces.

Roll angle was displayed from the zero point, at the top of the dial, clockwise through positive and negative angles, respectively, to a common 180 degree point. Pitch angle was displayed above and below the horizontal reference plane zero point, located at the nine o'clock position of the dial, from plus 90 degrees to minus 90 degrees. Yaw angle displacements were displayed to the left and right of the velocity vector represented by the zero point at the top of the dial through positive and negative angles, respectively, to the common 180-degree point.

Rate information was supplied by three separate rate meters, and a Collins ILS instrument provided vernier attitude information. The rate meters and the vernier instrument are described below.

Predictor display. A three-axis attitude angle predictor display was mechanized for this study, using the concept developed by Kelley (1960) and Kelley (1962). The predictor display presented the attitude of a symbolic spacecraft at three instants of time, as illustrated in Figures 3 and 4. The largest of the three symbols indicated the spacecraft's present attitude. The other two predicted time symbols were independently adjustable within a predicted time range from 7.5 to 240 seconds. The positions of the symbols predicting future spacecraft attitude were determined on the basis of the position and body rates of the present time symbol. As a result of pilot studies, prediction times of 10 seconds and 20 seconds were used in this study. The smallest symbol showed the spacecraft's attitude 20 seconds in the future and the middle symbol showed the spacecraft's attitude 10 seconds in the future.

The seven-inch cathode-ray tube display was scaled to show $\pm$ 180 degree yaw as full scale horizontal deflection ($\pm$3 inches), $\pm$90 degree pitch as full scale vertical deflection ($\pm$1 1/2 inches) and 360 degree roll by rotation of the symbols about their centers. A gain change, at the discretion of the pilot, was provided for operating when the spacecraft was within ten degrees of the reference axes in both pitch and yaw. The change permitted the expansion of the symbol size by a factor of three, and the angular displacements by a factor of twenty.

The analog computer mechanization for the prediction computation is shown in the Appendix. The mechanization was performed on two repetitive operation analog computers driven by initial conditions sampled from the main real-time mechanization. A description of the display generation equipment which processed the predicted data for display on the oscilloscope is also shown in the Appendix.

Vernier attitude displays. The vernier attitude displays for the three-axis attitude ball were integral to the instrument. For the predictor display, vernier indications were provided by a twenty to one gain change in predictor display deflection.

The Collins 329B-2 Approach Horizon Indicator was utilized as the vernier indicator for the individual axes display and the three-dimensional model display. The roll angle was indicated by the orientation of a bar and a perpendicular pointer. The pitch angle was indicated by the vertical displacement of a horizontal bar, and the yaw angle was indicated by the left-right deflection of the pointer at the top of the meter face. Full scale deflection of each pointer from zero corresponded to five degrees of vehicle attitude angle. Scale divisions were marked in one-degree increments for each angular indication.

Body rate displays. Body rate indications for the three-axis ball were provided by three meters clustered around the display. The body rate meters for the three-dimensional model and the individual axes displays were located beneath the respective dials of the individual axes display. The two sets of body rate meters were identical. They displayed full scale deflection from zero of plus or minus five degrees per second on a scale one and one-half inches long. For the predictor display, body rate information was inferred by examing the positions of the symbols predicting the spacecraft's attitude at future times.

Status displays. A time remaining readout was located at the upper right of the panel as shown in Figure 3. The three meters directly below the time remaining readout displayed the fuel consumed in percent, for roll, pitch and yaw. A hold light located above the time remaining readout notified the subjects when the computer was in a hold condition.

Hand controller. The three-axis hand controller was a standard B-8 grip used in the first phase of the program and was described fully in Volume I. Switches were positioned so that the on-off or the pulse modes could be actuated by any grip deflection in excess of approximately five degrees from zero.

For the single-pulse mode, the push-button on the controller was used for initiating pulses. The trigger on the hand controller was used to initiate pulses for the repeated pulse mode.

EXPLORATORY STUDIES

Exploratory studies were conducted to (1) familiarize pilot-subjects with the various display techniques being utilized, (2) select feasible ranges of display parameters being varied and (3) investigate display techniques and principles which could not be completely mechanized for comparative evaluation.

Subjects

Table 1 contains a summary of the flying experience of the pilot-engineers who participated as subjects in the display experiments. All subjects were current pilots with instrument ratings. During the training trials performance of individual subjects was monitored. When performance had stabilized at a high level of proficiency, the experimental runs were initiated.

TABLE 1.
FLYING EXPERIENCE AND AGE OF SUBJECTS

Subject	Flying Hours Military	Flying Hours Civilian	Age
A (LD)	1350	2000	33
B (EH)	1500	50	33
C (BN)	1400	300	40
D (BB)	1200	100	31
E (RN)	--	1200	30
F (JG)	2200	150	30
G (VP)	1400	50	30
H (BK)	2350	---	31
I (CS)	3500	3000	40

Maneuvers

The four attitude control maneuvers considered for use during these studies are described below:

1. Attitude Hold. Maintenance of an established vehicle orientation while the vehicle is subject to disturbance torques about the pitch and yaw axes.

2. Stabilization/Axis-Acquisition. Cancellation of the body rates of a tumbling vehicle in such a manner that the vehicle comes to rest in alignment with the desired reference system. This maneuver will be referred to hereafter as the stabilization maneuver.

3. Attitude Change. Rotation of the vehicle about three axes to change from one static orientation to another static orientation.

4. Rate-Nulling/Axis-Acquisition. Cancellation of the body rates of a vehicle tumbling toward alignment with the desired reference system. This maneuver was similar to the final steps of the stabilization maneuver. The initial conditions were selected so that the existing body rates were rotating the vehicle in such a manner that the vehicle axes would rotate within 20° of the reference system. The pilot's task was to selectively reduce the body rates so that alignment would occur on the first pass through the reference system axes. This maneuver will be referred to hereafter as the rate-nulling maneuver.

Display Deflection Thresholds

The vernier attitude and body rate meters were studied to determine the minimum change from zero which could be detected by a concentrating subject. The indicator under study was set to zero and slowly displaced from zero by a signal from the computer. The subject depressed one of two buttons indicating the direction of deflection as soon as a displacement could be detected. Depression of the corret button placed the computer into hold. If the incorrect button was depressed, the trial was repeated at the end of the series.

Subjects A, B, C and E received ten trials on each of three rates of deflection with direction of deflection and rates presented randomly for each of the indicators. Thus, each threshold was based on 120 observations. The deflection thresholds for each indicator are presented in Table 2.

TABLE 2.
DEFLECTION THRESHOLDS FOR SELECTED DISPLAY INDICATORS

Instrument	Axis	Threshold in Inches
Lear 4060C	Roll (Turn needle)	.0083
	Pitch	.0062
	Yaw	.0075
Collins	Roll	.0076
	Pitch	.0094
	Yaw	.0095
Body Rate Meters	Vertically Mounted	.0094
	Horizontally Mounted	.0074

Off-Axis Telescope Orientation

A problem of interest in manned spaceflight missions concerns the orientation of the optical axis of an observation telescope. With the telescope axis located off of the spacecraft control axes, the problem for the astronaut becomes one of controlling vehicle rotations in order to orient the telescope axis in some desired direction and to center and hold objects within the telescope field of view. The angular relationship between the spacecraft control axes and the telescope optical axis will determine the motion of objects within the telescope field of view as the spacecraft rotates. As these motions will not be consistent with motions on the attitude displays or objects viewed from windows, it is possible that an overlay grid, defining motion paths within the telescope field of view, could prove valuable to the astronaut in centering and holding objects in the telescope while he is rotating the vehicle.

An investigation of the utility of an overlay was undertaken. A dot representing a star was generated on a five-inch cathode-ray tube display. The motion of the dot represented the apparent motion of a star as viewed through a fixed, body-mounted telescope. The pilot's task was to rotate the spacecraft to bring the star to the center of the field of view. The motion of the dot to a control input was made to represent three locations of the telescope for both 1° and 10° fields of view:

1. The telescope optical axis aligned with the vehicle roll axis.

2. The telescope optical axis in the vehicle Y-Z plane at an angle 55° down from the Y-axis.

3. The telescope optical axis located at 30° azimuth and 60° elevation from the vehicle roll axis.

For this study eight initial positions of the star within the telescope field of view were used. The single-pulse mode of control was utilized. A result which appeared very early and very positively in these studies was that the pilots could readily learn the nature of the control-star movement relationships and center the simulated star as well without the aid of overlays as with them. This was an easily learned task and once the paths had been defined by the overlays and a few practice trials performed, the pilot could easily remember the motion relationships. No performance differences were found between the overlay and no-overlay conditions.

These results were somewhat surprising since it is generally assumed that the human is not very good at performing oblique, three-dimensional coordinate transformations. Implications of these results to the further definition of this problem will be discussed in the conclusions section.

Vertically-Referenced Attitude Display

A vertically-referenced attitude display seems to offer some advantages over a horizontally-referenced display during vertical maneuvers such as performed by the LEM, helicopters, VTOL and similar vehicles. In conventional vehicles, attitude control is concerned primarily with alignment of the vehicle longitudinal and lateral axes with the local horizontal. In vertical maneuvers, attitude control is largely concerned with aligning the lift or thrust vectors or the vehicle vertical axis to the local vertical. Although alignment of the vertical axis with the local vertical can be determined from a horizontally referenced attitude indicator, it would seem more appropriate to display this relationship to the astronaut directly rather than require him to perform a coordinate transformation.

An artist's concept of a vertically-referenced attitude display is presented in Figure 5. The display is viewed from above and appears as if the top hemisphere were removed from a conventional ball attitude display. The visible surface of the remaining hemisphere becomes a direct mechanical analog of the landing surface. As the vehicle pitches forward, the forward horizon rotates upward and as the vehicle rolls to the right, the right horizon rotates upward.

Four meridian lines rigidly mounted to the landing surface of the display intersect at what would be the top pole of a conventional attitude ball. Roll and pitch angles are read at the apex of the display by reference to indices inscribed on the transparent hemispherical cover. Thus, both roll and pitch are displayed as a single point on a polar-coordinate reference system.

By mounting the rate indicators to the display platform, they are referenced to the instantaneous spacecraft attitude. As the body rate indicators deflect from the intersection point of the meridians, they indicate the direction of travel of the local vertical relative to the vehicle's vertical axis. As the landing surface and its meridian lines rotate the rate indicators rotate with them. When the rate indicators arrive under the desired attitude position, the body rates can be reduced to hold the rate indicators on this point. This allows a smooth exponential decay of attitude rates to arrive at the desired position with zero attitude rates. Both the attitude and rate indications are "fly-to" or "inside-out" in that the zero reference marks are flown toward the moving indices to cancel misalignments and errors.

At this writing, a vertically-referenced attitude display exists only in concept. To test the feasibility of the vertically-referenced and attitude-referenced body rate principles, an experimental simulation of the display was undertaken. The display was simulated by representing the intersection of the meridian lines by a dot on a five-inch cathode-ray tube. An overlay on the CRT represented the markings on the hemispherical cover glass. The intersection of the body rate indicators was represented by a small circle on the cathode-ray tube display. The maneuver performed was simulated hover, which consisted

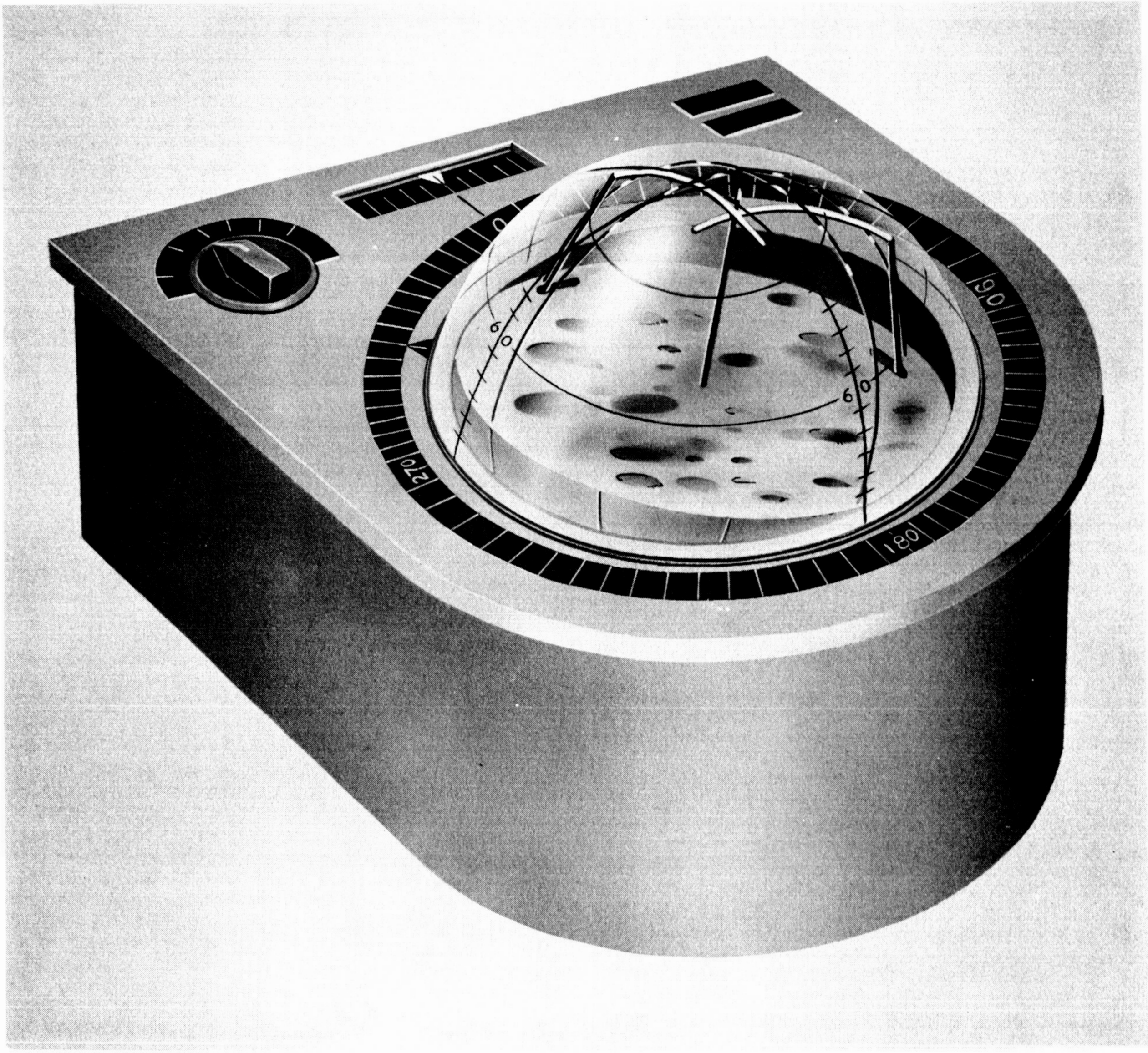

Figure 5. Artist's Conception of the Vertically-Referenced Attitude Display

of the attitude hold maneuver with the disturbance torques introduced about the pitch and roll axes instead of the pitch and yaw axes. Pilots A, B, C, F, G and H each performed 20 experimental trials utilizing the on-off acceleration control mode. The lower level of disturbance torque was utilized and the control system torque was set at 3.33 times the peak disturbance torque. System performance was measured in terms of accuracy (rms angular error) throughout each 90-second trial.

Figure 6 contains the results of this preliminary investigation. The six points plotted at the 3.33 torque advantage ratio level represent the average for each of the pilots. The performance curve plotted is reproduced from Volume I (page 32, Figure 16) and represents performance on the same task using conventional attitude and body rate indications. It can be seen that the performance of five of the six pilots was considerably improved over the performance using conventional attitude indicators. The sixth pilot had performance nearly identical to performance with the conventional instruments. In addition, the scale factor of the vertically-referenced instrument was less than half as sensitive for the vertically-referenced display as for the conventional display. If the scale factors had been comparable an even greater performance advantage for the vertically-referenced display should have resulted.

Although this data is by no means conclusive, it does indicate that the principles of vertically-referenced attitude and attitude-referenced body rates do offer definite improvements in performance and an attitude presentation using these principles warrants further investigation.

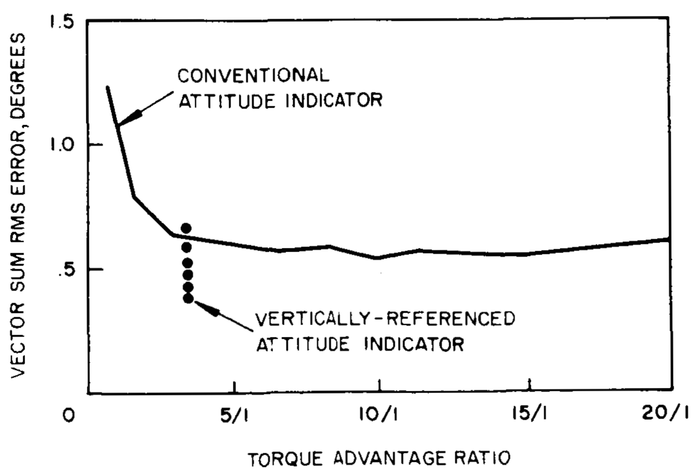

Figure 6. Comparison of Attitude Hold Accuracies Between Conventional and Vertically-Referenced Attitude Displays

EXPERIMENTAL STUDIES

Two main experimental programs were conducted during this phase. The first was concerned with the effects of display gain or scale factor on system perforance and the second was concerned with measuring and comparing system performance resulting from various types of situational attitude displays.

Display Gain Study

Experimental studies were conducted to determine the relationship between display scale factor and system performance on the attitude hold and the rate-nulling maneuvers. In addition, an attempt was made to normalize display scale factor in terms of the ratios between scale factor and disturbing torques and between optimum scale factor and just noticeable deviation (j.n.d) on the display.

The scale factors were varied on the vernier attitude needles of the three-axis attitude ball. Maximum deflection of the needles was one inch. Preliminary studies revealed that a range of scale factors between 0.5 degree/inch and 10 degrees/inch was feasible. Below 0.5 degree/inch, the scale factor was too sensitive and system performance deteriorated due to rapid limit cycle operation. The angular coverage provided by the display was too small to allow rate cancellation between the time the needle came off the limit on one side and reached the limit on the other side. The upper limit of the vernier scale factor was approximately the scale factor of the attitude ball.

Maneuvers. The rate-nulling and attitude hold maneuvers were performed. The rate-nulling maneuver was initiated from plus or minus 45 degree attitude angles in roll, pitch, and yaw and with body rates of 2.0 degree/sec about each axis. Eight combinations of initial attitude angles and initial body rates were used.

The subjects were instructed to stabilize the vehicle to within 1.0 degree of the reference axes with less than 0.1 degree/sec body rates. This was to be accomplished within a 180-second time period with minimum fuel expenditure. The computer was placed in a hold condition automatically when all of the angles and body rates were simultaneously within the specified limits. A single-pulse mode of control was used with 0.086 degree/sec per pulse. The performance measure was the integral of the absolute values of commanded accelerations. These integrals can be converted to pounds of fuel consumed. See Volume I and Bauerschmidt and Besco (1962).

In the attitude hold maneuver the subjects were instructed to maintain a zero attitude error between the instantaneous vehicle attitude and the reference system axes while the vehicle was subject to random disturbance torques (rms of

.154 degree/sec^2) about the pitch and yaw axes. Fifteen seconds after the beginning of the trial the computations of rms angular error and fuel consumption were started automatically. The scored portion of the trial lasted 90 seconds. An on-off mode of control was used with the control system torque set at 3.33 times the peak disturbance torques. The performance measures were the vector sum of the pitch and yaw rms angular error components and the integral of the absolute value of commanded accelerations.

Data reduction. The data analyses employed analysis of variance procedures. Appropriate F ratios were derived by the procedure suggested by Winer (1962).

Experimental design. Subjects A, B, D and I were used. Two of the pilots started using the highest scale factor, performed two consecutive stabilization trials and two consecutive tracking trials at each scale factor in a descending order down to the lowest scale factor and progressed up to the highest and back down. The eight initial condition combinations of attitude angles and body rates were randomized within each block of eight stabilization trials for each subject. The performance estimate for each scale factor and maneuver combination was based on sixteen observations (4 trials for each of 4 subjects). This resulted in three complete 4 by 12 random model factorial designs with subjects and scale factors as the experimental variables.

Results. The results of the three performance measures on the two maneuvers were treated independently. The data analyses, using analysis of variance procedures for the three performance measures, are summarized in Tables 3, 4, and 5. Effects on system performance caused by changes in vernier scale factors were significant beyond the .01 level on the vector sums of the rms error for the attitude hold maneuver and beyond the .10 level on the fuel index for the rate-nulling maneuver. Subjects was a significant variable beyond the .01 level for all three measures. Figure 7 contains the plot of system performance for the various scale factors. The fuel consumption and the rms error were greatest at the upper and lower ranges of the scale factors. Thus, the optimum region for full scale deflection of the verniers for these maneuvers would seem to lie somewhere between 0.75 degree/inch and 2.0 degree/inch. Further interpretation of these results will be given in the discussion section.

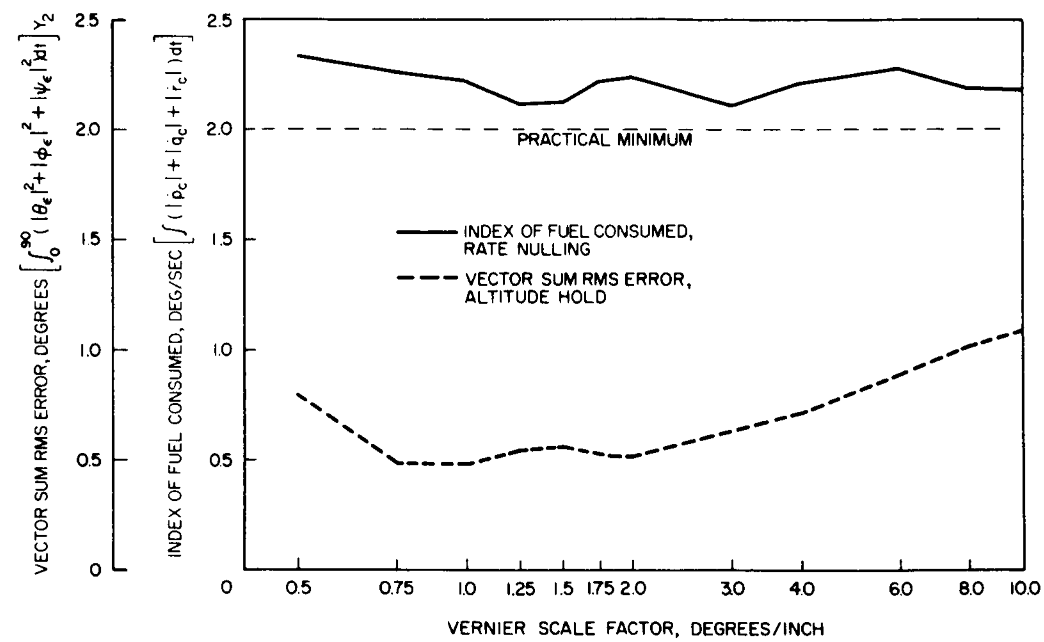

Figure 7. System Performance as a Function of Scale Factors for Both Maneuvers

TABLE 3.
ANALYSIS OF VARIANCE SUMMARY: RMS ERROR ON THE ATTITUDE HOLD MANEUVER, DISPLAY GAIN STUDY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Subjects (A)	4.3813	3	1.4604	18.58***
Scale Factors (B)	7.8130	11	.7103	9.04***
AB	2.5934	33	.0786	1.16
Experimental Error (within cell)	9.7209	144	.0675	

TABLE 4.
ANALYSIS OF VARIANCE SUMMARY: INDEX OF FUEL CONSUMED ON THE ATTITUDE HOLD MANEUVER, DISPLAY GAIN STUDY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Subjects (A)	129.4655	3	43.1552	15.30***
Scale Factors (B)	31.8474	11	2.8952	1.03
AB	93.0955	33	2.8211	.53
Experimental Error (within cell)	771.8773	144	5.3603	

TABLE 5.
ANALYSIS OF VARIANCE SUMMARY: INDEX OF FUEL CONSUMED ON THE RATE-NULLING MANEUVER, DISPLAY GAIN STUDY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Subjects (A)	413.4920	3	137.8307	33.20***
Scale Factors (B)	84.7290	11	7.7026	1.86*
AB	137.1643	33	4.1565	.38
Experimental Error (within cell)	1567.2242	144	10.8835	

n = 4
A and B were considered to be random treatment effects.
*** Significant at the .01 level
** Significant at the .05 level
* Significant at the .10 level

Display Comparison Study

Four types of displays, representing different means of presenting the same attitude information, were compared in this study. The purpose was to evaluate the resulting system performance when using the various displays. The displays utilized to represent these four types were chosen primarily on the basis of availability.

The four display types, described previously in this report, were: (1) the three-axis attitude ball display, (2) the individual axes display, (3) the predictor display and (4) the three-dimensional model display. The scale factors on all of these displays were practically identical.

The three-axis attitude ball represented the type of attitude presentation to be used in the Gemini and Apollo vehicles. The display provided an integrated, all-axis, inside-out presentation, which is to a large degree an outgrowth of conventional aircraft attitude displays.

The individual axes display represented the type of presentation used in the Mercury spacecraft. It presented the attitude angle of each axis on a separate meter and could be mechanized for either an "inside-out" or "outside-in" presentation. In this study it was mechanized as an "outside-in" display to conform to the Mercury capsule configuration. This type of display has received emphasis in space programs because of its mechanization simplicity, low weight and low power consumption.

The predictor display was a development of Kelley (1962), and has been received with considerable interest in research studies by display and control system designers. It provided an integrated, all-axis presentation. The predictor could be mechanized for either an "inside-out" or an "outside-in" presentation. In this study, it was mechanized an an "outside-in" display, primarily due to the ease of mechanization of this mode.

The three-dimensional model display was first suggested by Hopkins and Bauerschmidt (1960) for use primarily in spacecraft. It provided an integrated, all-axis, "outside-in" presentation. The particular model used here was a breadboard model developed previously to demonstrate the feasibility of this type of display.

<u>Control system</u>. The on-off acceleration mode of control was used for the attitude hold maneuver. The single pulse and repeated pulse modes of control were used for the attitude change and the stabilization maneuvers. The exact parameters for these modes were described in the Simulation Section.

Experimental procedure. Subjects A, B, D and E received twelve consecutive trials using each of the four displays. These twelve trials consisted of four consecutive stabilization maneuvers, four attitude change maneuvers and four tracking maneuvers. The order of presenting the displays and maneuvers was counterbalanced between subjects. For the stabilization maneuver, sixteen initial condition combinations of attitude angles and body rates were used. The list was presented in a random order to each subject. Eight initial condition combinations of attitude angles were used for the attitude change maneuver. The list was randomized within each block of eight trials for each subject. The performance estimate for each maneuver and display combination was based on sixteen observations (four trials for each of four subjects). This resulted in three complete four by four factorial designs with displays and subjects as the experimental variables. Subjects was considered a random treatment effect and displays a fixed effect.

Results. The results of the analyses of variance for the attitude hold maneuver are summarized in Tables 6 and 7 for the fuel consumption and the rms error scores, respectively. The effect due to displays, the effect due to subjects, and the displays by subject interaction caused significant variations in fuel consumption at the .01 level. When using the index of fuel consumed as a performance measure, individual comparisons showed that the predictor performed better than the three-axis ball or the three-dimensional model displays at the .01 level, and better than the individual axes display at the .05 level. Also, individual comparisons showed that the three-dimensional model display required more fuel than the three-axis ball (.10 level) or the individual axes display (.05 level). Analysis of the rms error scores showed the differences between displays were significant at the .05 level, and the variations between subjects were significant at the .01 level. The displays by subjects interaction was also significant. Individual comparisons showed the error scores for the predictor were significantly less than those for the other three displays (.01 level). Figures 8 and 9 show mean performance on each display for fuel consumption and rms error scores, respectively.

TABLE 6.
ANALYSIS OF VARIANCE SUMMARY: INDEX OF FUEL CONSUMED ON THE ATTITUDE HOLD MANEUVER, DISPLAY COMPARISON STUDY

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F
Displays (A)	134.1410	3	44.7137	7.51***
Subjects (B)	115.2870	3	38.4290	22.14***
AB	53.6150	9	5.9572	3.43***
Experimental Error	83.3015	48	1.7354	

TABLE 7.
ANALYSIS OF VARIANCE SUMMARY: RMS ERROR ON THE ATTITUDE HOLD MANEUVER, DISPLAY COMPARISON STUDY

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F
Displays (A)	.2899	3	.0966	4.89**
Subjects (B)	.0649	3	.0216	5.26***
AB	.1777	9	.0197	4.80***
Experimental Error	.1975	48	.0041	

n = 4
A was considered to be a fixed treatment effect.
B was considered to be a random treatment effect.
*** Significant at the .01 level.
** Significant at the .05 level.

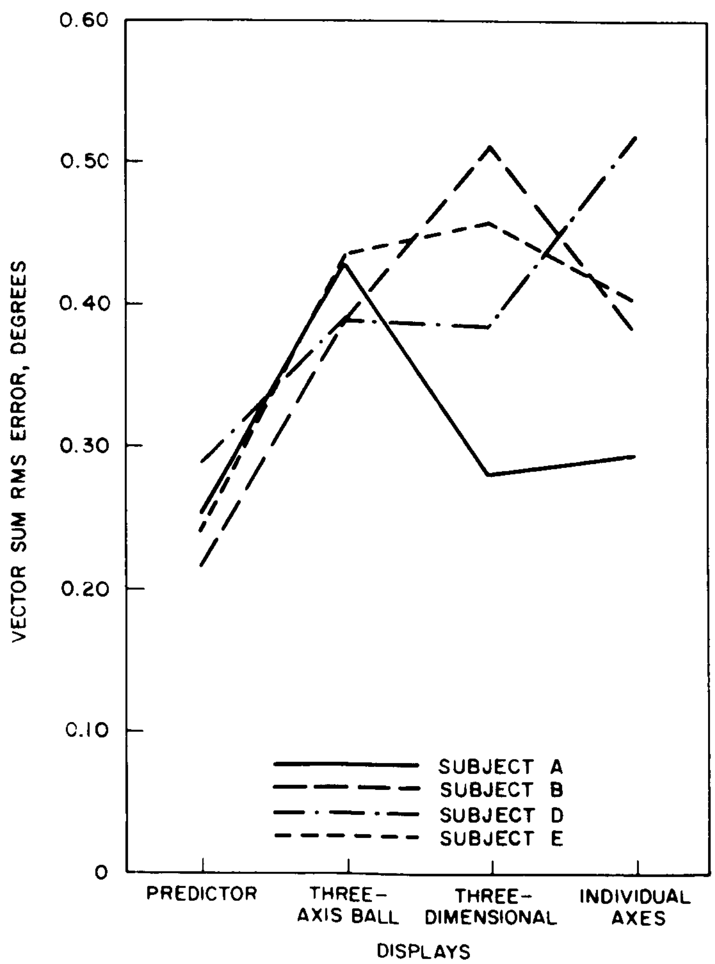

Figure 8. RMS Error Scores on the Attitude Hold Maneuver for Each Display

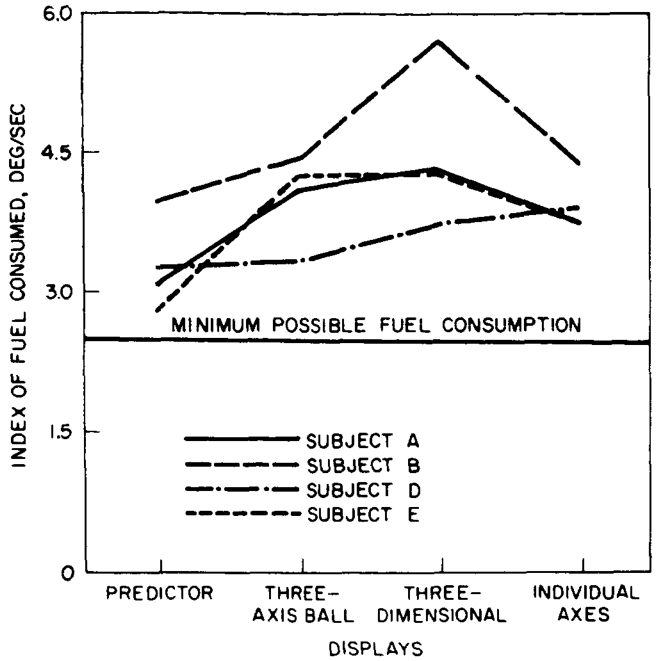

Figure 9. Fuel Consumption on the Attitude Hold Maneuver for Each Display

Tables 8 and 9 contain the results of the analyses of variance for the stabilization maneuver and the attitude change maneuver. The index of fuel consumed was the performance measure for both maneuvers. The only significant variance for both maneuvers was that caused by differences between subjects.

TABLE 8.
ANALYSIS OF VARIANCE SUMMARY: INDEX OF FUEL CONSUMED ON THE STABILIZATION MANEUVER, DISPLAY COMPARISON STUDY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Displays (A)	1.078	3	.3593	.07
Subjects (B)	97.082	3	32.3607	5.89***
Error (pooled)	313.4186	57	5.4986	

TABLE 9.
ANALYSIS OF VARIANCE SUMMARY: INDEX OF FUEL CONSUMED ON THE ATTITUDE CHANGE MANEUVER, DISPLAY COMPARISON STUDY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Displays (A)	2.3326	3	.775	2.10
Subjects (B)	10.1163	3	3.372	9.12***
AB	2.9378	9	.3264	.86
Error (pooled)	21.0813	57	.3698	

n = 4
A was considered to be a fixed treatment effect.
B was considered to be a random treatment effect.
***Significant at the .01 level.

After the study was completed a display preference survey was conducted. Each subject was given a set of eighteen cards with one of the three maneuvers and two of the four displays listed on each. Thus, there were six possible combinations of displays for each of three maneuvers. The subject was instructed to choose which of the two displays he would prefer in order to perform the particular maneuver listed on each card. He was instructed to use the operational utility of the display as a criterion for making his selection. For each maneuver, any display could be preferred a maximum of 12 times (preferred over the other three displays by each of the four pilots). The subjects' preferences between displays for each maneuver and the overall percentages are contained in Table 10. Across all three maneuvers, the predictor display was preferred 94.4% of the time, the three-axis ball was preferred 63.9% of the time, the three-dimensional display was preferred 38.9% of the time and the individual axis display was preferred only 2.8% of the time. The percentage of agreement between subjects on their choice of displays was 91.7%.

TABLE 10.
RELATIVE FREQUENCIES OF PILOT PREFERENCES FOR THE DISPLAYS ON EACH MANEUVER

Displays	Attitude Hold	Stabilization	Attitude Change	Overall %
Predictor	12	11	11	94.4%
Three-Axis Ball	8	8	7	63.9%
Three-Dimensional	3	5	6	38.9%
Individual Axes	1	0	0	2.8%

DISCUSSION

This section of the report contains brief discussions, interpretations and recommendations of the results of the exploratory and experimental studies. Some suggested principles and guidelines for display system designs are also outlined.

Off-Axis Telescope Orientation

The results of the preliminary investigations suggest that a skilled pilot can readily learn and recall, at least on a short-term basis, the complex and unconventional motions across an off-axis field of view. It seems that, for fixed or limited locations of telescopes relative to control axes, no overlay or scribe line aids would be required on relatively short missions. It still remains to be determined how well the motion paths could be recalled after long periods. In most spacecraft in which off-axis telescopes would be mounted, the telescope would most likely be used at least daily. There would probably be no requirement for long term retention of motion paths and the associated control skills.

Of even greater interest would be the number of telescope orientations and the magnitude of the angular differences in location between these locations which could be learned, remembered and recalled by an astronaut. More data is needed about the effects on attitude control system performance of (1) the number of discrete locations and (2) the angular magnitude through which a telescope can be slewed.

Vertically-Referenced Attitude Display

The results of the study on the vertically-referenced attitude indicator indicated that the display could enhance control of the pitch and roll axes during hover and vertical maneuvers. The principle of attitude referenced body rates provides an integrated presentation which is both situational and "quickened" (see Birmingham and Taylor, 1954). The separation of the position and rate symbols allows the pilot to select any rate of return to zero error and does not depend on a damping factor which is optimized for a particular maneuver or set of conditions.

The entire display configuration was designed to maximize performance during vertical maneuvers. It still remains to be demonstrated that the concept is adequate for other required maneuvers such as docking, alignment for retrofire, etc.

Display Gain Study

There was a decided improvement in performance on the tracking maneuver when the display scale factor was between 0.75 degree/inch and 2 degree/inch. This scale factor range provided adequate resolution and allowed the pilots to keep their control movements well below one cycle per second. From Figure 5 it can be seen that there was a decided decrement below 0.75 degree/inch. At a full scale of ± 0.5 degree/inch, the operator had to operate the control at nearly one cycle per second a great deal of the time to prevent the displayed error from limiting. Consequently he would get out of phase with excursions in the displayed error. This was considered to be the major cause of the performance decrement with this scale factor.

It was demonstrated that for maneuvers requring low-frequency control actuation such as attitude change, stabilization and rate-nulling, the scale factor on the display was not a critical variable to system performance. Qualitatively, the pilots expressed a preference for displays with a scale factor from 2 degee/inch to 5 degree/inch for these maneuvers. This scale factor allowed enough resolution so that the tolerance bands of one degree could be easily read. Also, there was enough range so that rates could be cancelled between the time that the needle came out of limit and the time it crossed zero.

It was observed during these studies that optimum display gain or scale factor was also dependent on the total range of display. For a display with a fixed scale factor these two variables are inversely proportional and the optimum scale factor has to be a trade-off between the optimum values of both scale factor and range.

The attempt to normalize scale factor with either display deviation thresholds, disturbance torques or pilot response frequencies was not successful.

Display Comparisons

For the attitude hold or tracking maneuver, the predictor display was clearly superior to the other threee types of displays, both in terms of accuracy and fuel consumption. This superiority was achieved inspite of two conditions which should have placed the predictor display at a disadvantage. First, the predictor format was the least familiar format to the pilot subjects. Two, the vernier scale factor on the predictor (2.5 degree/inch) was slightly less sensitive than the scale factor for the other three displays (2.0 degree/inch). From Figure 7 it can be seen that tracking performance should be less accurate at the higher scale factor; however, predictor performance clearly overshadowed this disadvantage.

The qualitative comments from the pilots indicated that the superior performance and pilot preferences for the predictor resulted from one primary principle of the display. This principle has been termed the "attitude-referenced-rate" principle. This principle embodies two features which enhance tracking performance. One, the display is in a sense both quickened and situational. The future time symbols deviate from the present time symbol as a function of derivative or rate information. This allows the pilot to null rates before attitude has deviated and also allows the pilot to select his own quickening or damping coefficients when nulling a large attitude error. The second feature is that the format used allowed the rate and vernier attitude to be presented integrally in the same location, thus greatly reducing the pilot eye scan or cross-check burden. The combined vernier attitude-body rate presentation would add considerable mechanization complexities to the other three display formats.

The above arguments in favor of the predictor display do not preclude the use of the other displays when overall system effectiveness is considered. The three-axis ball certainly offers advantages in terms of pilot familiarity, proven off-the-shelf mechanization techniques and consistency of motion with an external field of view. The individual axes display offers light-weight, low-power consumption, and mechanization simplicity advantages with disadvantages in increased panel area and a more abstract presentation. The three dimensional model offers advantages for remote control of unmanned shuttle vehicles where this display now becomes consistent with motions in the external field of view.

CONCLUSIONS

The principle of "attitude-referenced-body rates", which was embodied in the predictor display used in this study, was demonstrated to offer marked advantages for tracking accuracy and fuel efficiency. Mechanization techniques to enable the incorporation of this principle into other types of attitude, trajectory and other vehicular control displays should be investigated.

The data reported herein support the conclusion that information content, display range and display resolution are more critical variables in display design than display format variables. Pilots demonstrated a marked preference for integrated displays with an analog format. Although differences between display formats were large and statistically significant, other system considerations do not eliminate any of these four types for consideration in future spacecraft.

March 1964
HUGHES AIRCRAFT COMPANY
Culver City, California

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APPENDIX

PREDICTOR DISPLAY MECHANIZATION

APPENDIX

PREDICTOR DISPLAY MECHANIZATION

INTRODUCTION

This appendix describes the analog computer and electronic circuit mechanization which was used during this study for the evaluation of the predictor concept.

The spacecraft predictor display configuration that has been chosen for this study has been described in the body of this report. The spacecraft predictor utilized a panel-mounted seven-inch cathode ray tube (CRT) which displayed symbols representing the spacecraft's roll, pitch and yaw orientation at the present and two future instants of time. These symbols were electronically generated and were positioned by the output of a fast-time analog computer.

The display symbol generator permitted the choice of a variety of display symbology made up of simple line elements. In addition, the mechanization permitted the adjustment of the size of each symbol from zero to the full CRT diameter. The intensity of each symbol was varied to compensate for changes in symbol size.

Since the effect of prediction time upon system performance was to be evaluated during this study, fast-time computer mechanization provided a ready means of altering the prediction time for each symbol.

The functional block diagram shown in Figure A1 illustrates the spacecraft predictor mechanization and operation. The system contained two independent time standards. One clock determined the prediction time of the fast-time analog computations and had an adjustable period that could be selected by the experimenter. The other clock operated at high speed and was used to trigger the display symbol generator to write recurrent display data frames at 60 cps.

The predicted display symbol coordinates and the predicted sine and cosine of roll angle used to rotate the symbols were held in a track store unit for the duration of each prediction cycle. The track store unit was interrogated by the display sampling gates at a 240 cps rate. The sequential output of the display sampling gates provided:

1. Signals for the orientation of each of the predictor symbols.

2. Vertical deflection corresponding to the predicted pitch angle for each symbol.

3. Horizontal deflection corresponding to the predicted yaw angle for each symbol.

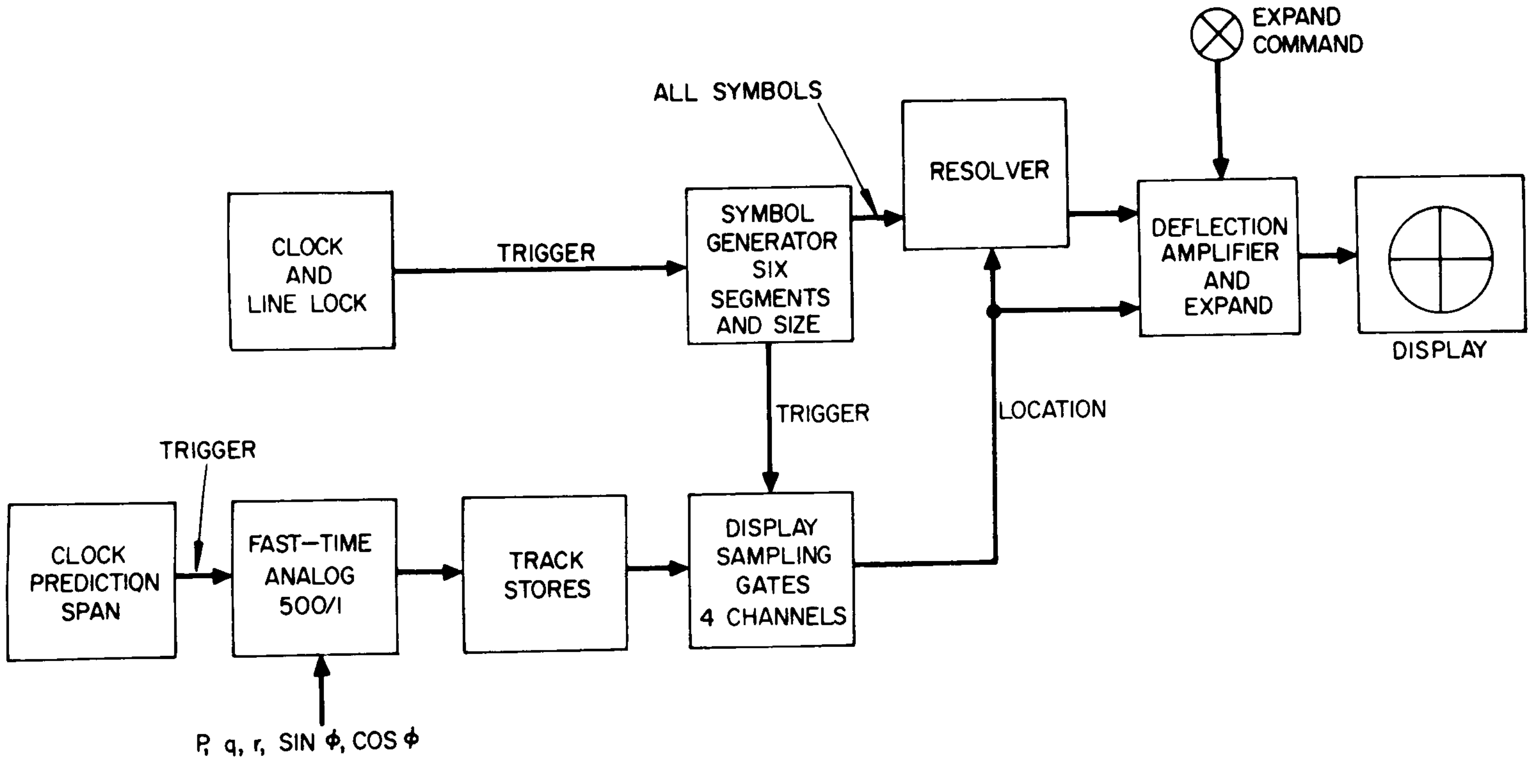

Figure A1. Predictor Display Functional Block Diagram

CIRCUIT DESCRIPTION

A detailed circuit block diagram is shown in Figure A2. A trigger from the clock output J-6 pulsed a scale-of-eight binary counter which was decoded to a sequential count via the symbol decoding matrix and forced to count six. The count of six was accomplished by driving all the counter reset lines with decimal six. In order to have a six output from the decoding matrix, a special matrix column sensed the reset condition (normal eight count) and supplied it during the sixth interval.

The six sequential decoded pulses were reformed via the dual inverter modules into the standard 15 volt logic level and its complement. These outputs were available at patching jacks for subsequent use in generating the display symbology. A basic symbol of maximum display size was constructed according to the patching sequence used by the experimenter (Figures A3 and A4 illustrate the results of the process).

The integrated pedestal levels in X and Y were linear deflection signals whose slope was proportional to the pedestal input amplitude to the integrator. Because of the display requirement for three different sizes of space vehicle symbols, the integrator outputs were patched to the X and Y size controls which permitted continuous setting of the symbol size and aspect ratio by the operator. The size control outputs were impedance transformed via the buffer section and applied to the transmission gate inputs. The sequential output of the transmission gates was buffered by two operational amplifiers in cascade, which made both polarities of the output signal available for subsequent processing by the display resolver and deflection summing circuitry.

A third block of gating circuits, identical to that previously described, was used to produce unblanking pedestals for each of the display symbols. Adjustment of the unblanking level was necessary to compensate for variations in the phosphor duty cycle that occurred as a result of symbol size changes. The remaining transmission gates sampled the computed pitch, roll and yaw quantities for further processing by the symbol resolver and deflection outputs group.

The line-lock feature of the symbol generator, Figure A2, J-5, J-7 was included for the purpose of negating the effects of 60 cps-based-ripple in the remote display equipment. The line-lock feature operated as follows. At the conclusion of the fourth displayed symbol the gating pulse reset the master trigger binary to a state that inhibited the output gate of the system clock. The system trigger was prevented from initiating further generator action until the master trigger was set. The next 60 cps line period triggered a Schmitt circuit which set the master trigger, permitting the symbol generation to proceed.

The mechanism for displaying symbol roll and display coordinate location is illustrated in Figure A5. The sampled computed attitude variables from the present-time and fast-time computations were applied to the resolver and deflection amplifiers. The Y and X deflection amplifier outputs were in turn sent to the monitor and simulator CRT displays.

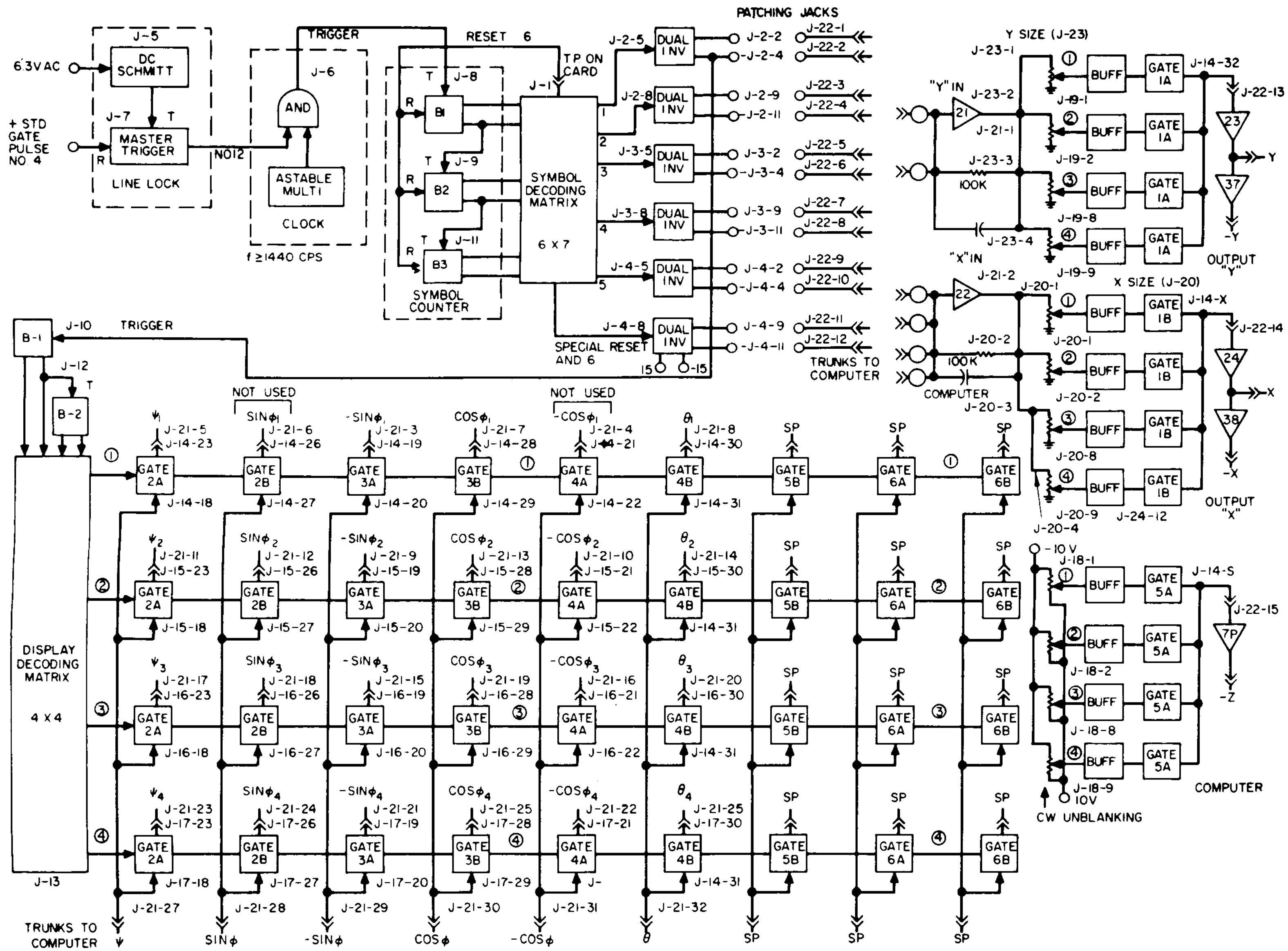

Figure A2. Predictor Display Generator Block Diagram

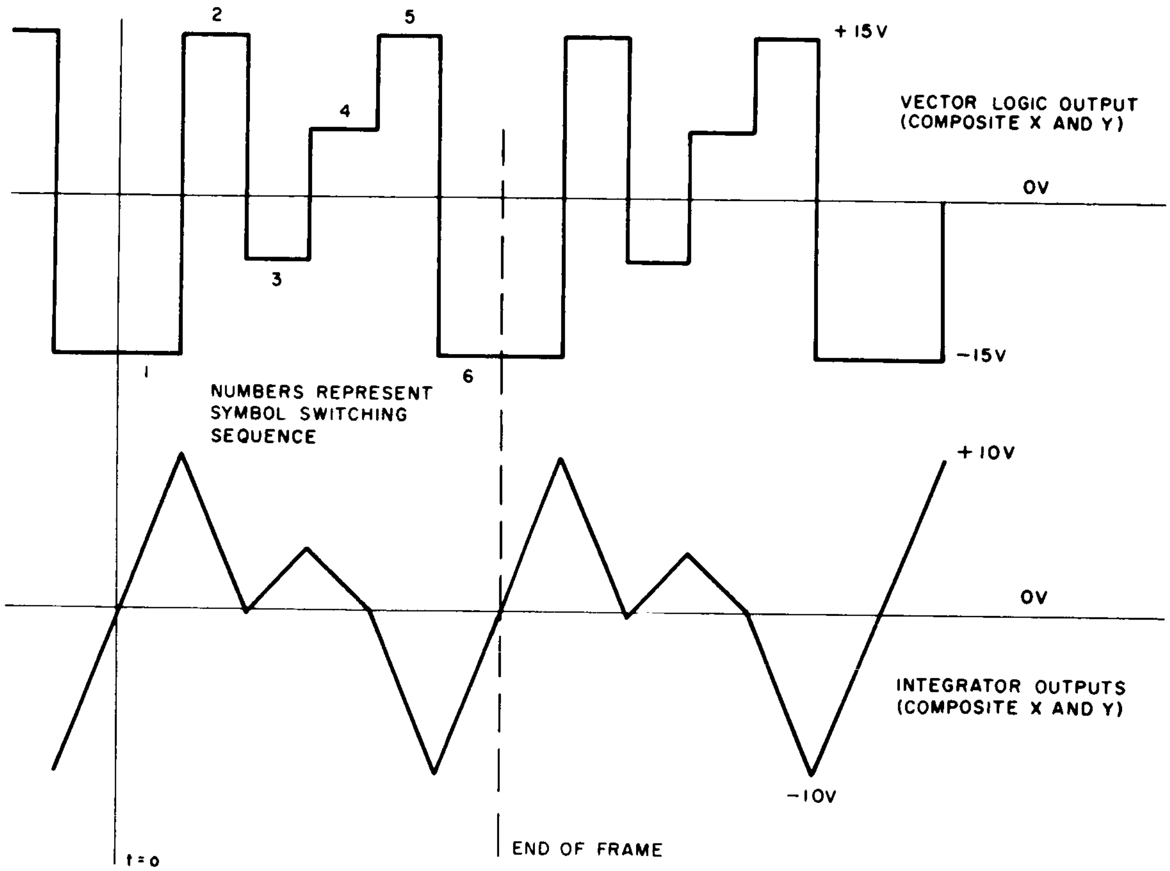

Figure A3. Symbol Generator Waveforms

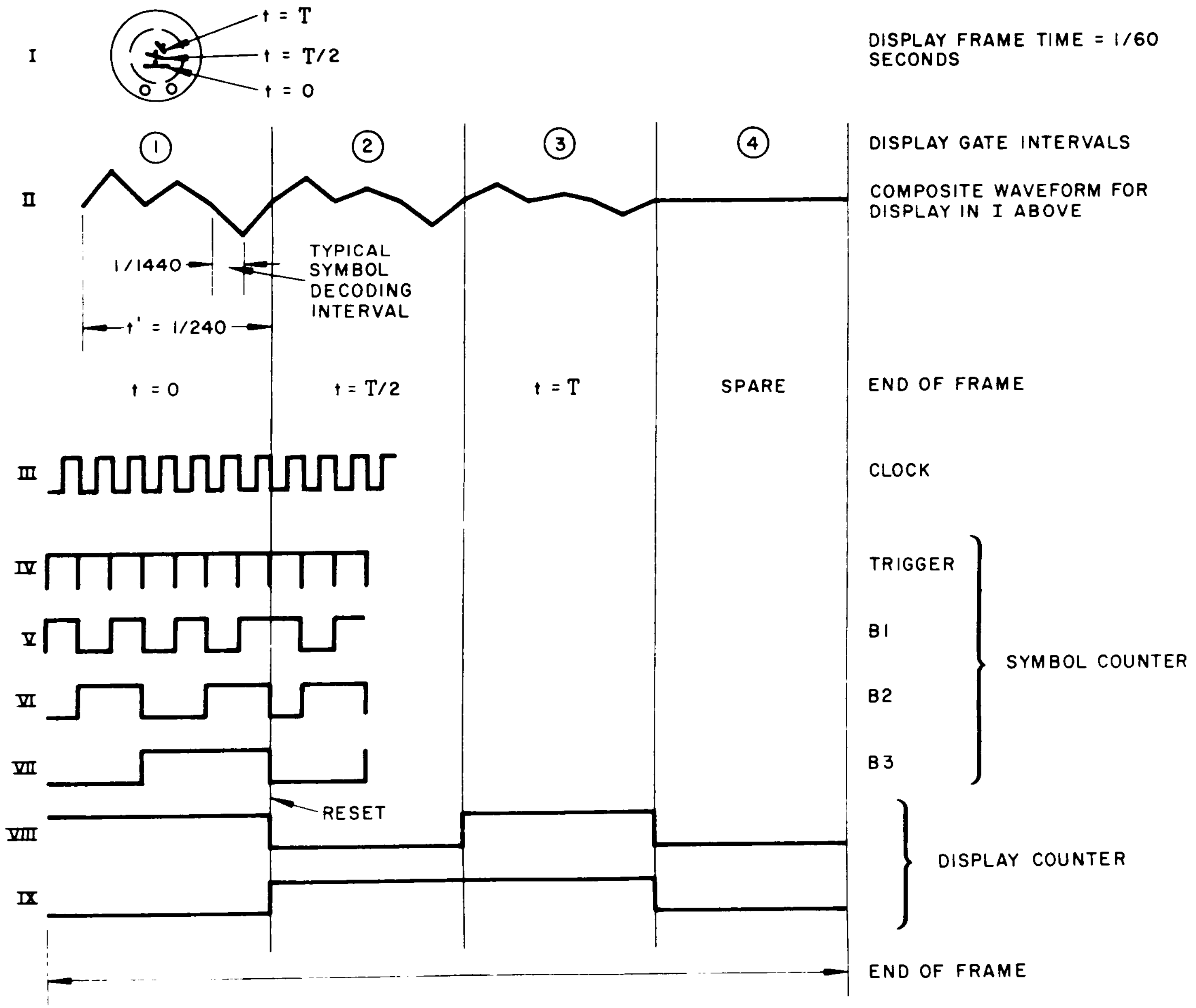

Figure A4. Predictor Timing Diagram

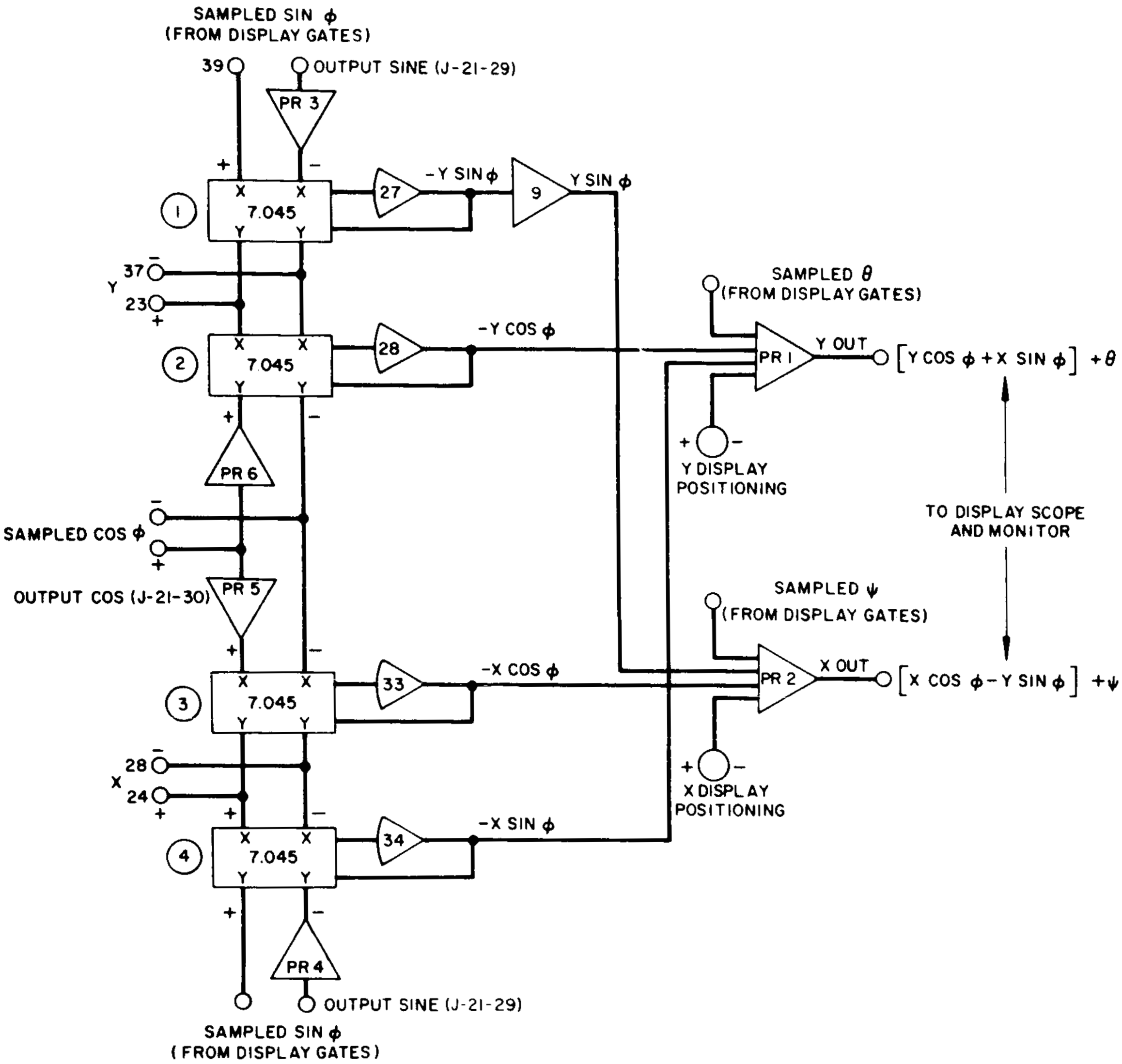

Figure A5. Predictor Symbol Resolver and Deflection Outputs

PREDICTION COMPUTER

The computer schematic diagrams appear in Figures A5, A6 and A6a, Figures A6 and A6a are indicative of the predictive technique, while Figure A5 illustrates the high-speed resolver technique.

The prediction computer computations were performed on an Electronic Associates Model TR-10 Analog Computer capable of repetitive operation. The prediction span or computer-operate interval was chosen by the experimenter based upon the fast-time analog scaling. This scaling represented a speed increase of 500 over the real-time problem computation.

The body angular rates ($\dot{p}$, $\dot{q}$ and $\dot{r}$) were continuously supplied to the fast-time analog largely by the equipment of Figure A6 which solved the following equations:

$$\dot{\phi} = p + \dot{\psi} \text{ Sin } \theta \qquad \text{(A1)}$$

$$\dot{\theta} = q \text{ Cos } \phi - r \text{ Sin } \phi \qquad \text{(A2)}$$

$$\dot{\psi} = (q \text{ Sin } \phi + r \text{ Cos } \phi) \frac{1}{\text{Cos } \theta} \qquad \text{(A3)}$$

In turn, the fast-time or repetitive analog solved for the predicted values of p, q, r, Sin ϕ and Cos ϕ. The instantaneous value of these variables was held within track store units, for subsequent readout by the display sampling unit. The track store unit as illustrated in Figure A6a, was an analog storage device where the storage period was equal to the computer operate time.

Although this system was fairly wasteful of components, it had two advantages for solution of the predictor problem:

1. Small variations in predicted quantities (normally appearing as noise) were eliminated over the store span.

2. The track store interval was directly proportional to the predicted value of the vehicle attitude with respect to time.

As a consequence of (2) above, the number of predicted symbols could be increased directly by increasing the number of storage units.

The output of the resolver consisted of all the vehicle analog symbols scaled in size and appropriately oriented. The resolver signal was summed with the sampled pitch and yaw signals at the deflection amplifiers, which served as line drivers for the simulator displays and computer room monitor.

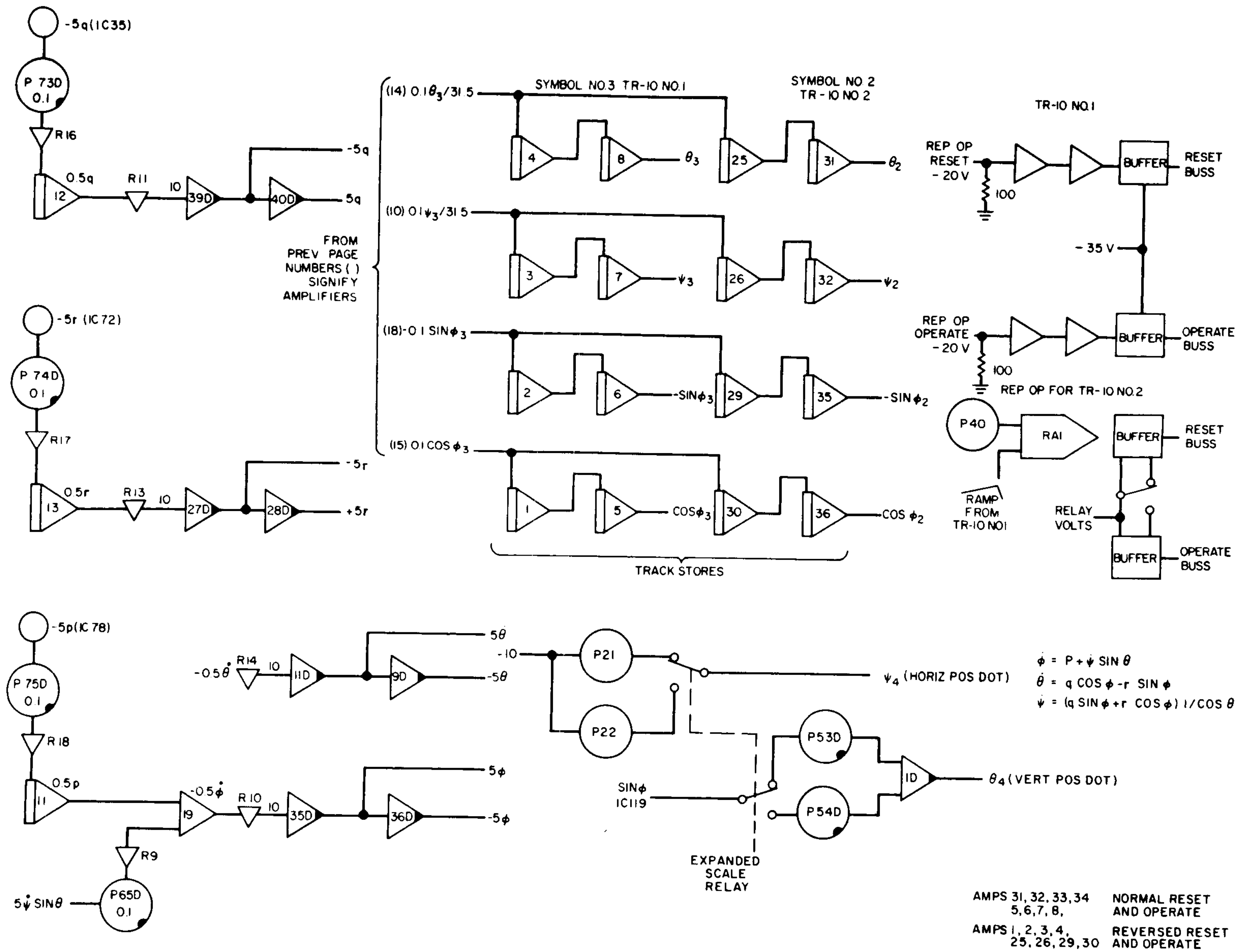

Figure A6. Fast-Time Analog Computer Schematic

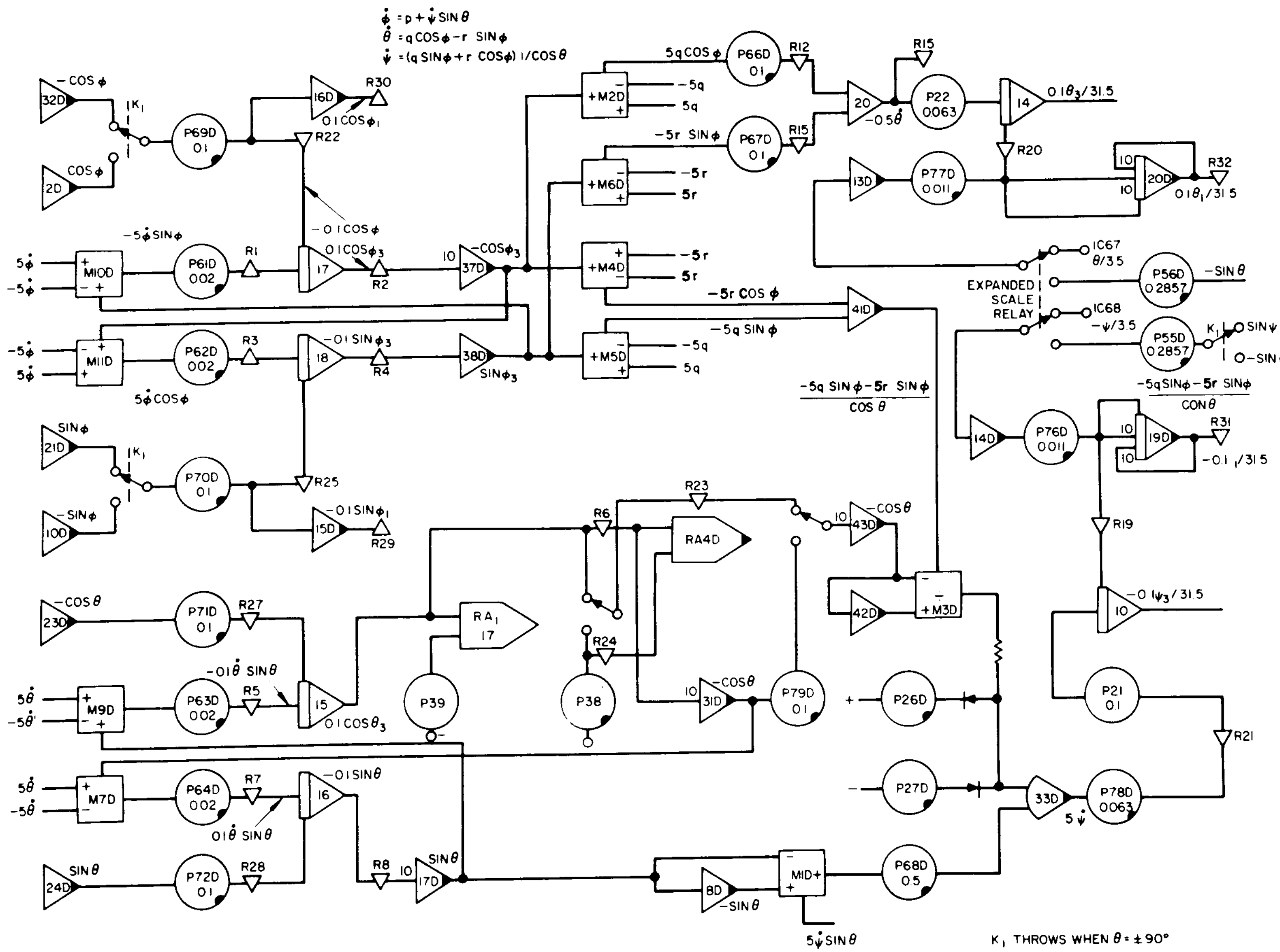

Figure A6a. Fast-Time Analog Computer Schematic (Continued)

LIST OF SYMBOLS

Symbol	Definition	Units
I_{xx}, I_{yy}, I_{zz}	Moments of inertia about the body axes.	ft-lbs/sec^2
p, q, r	Scalar components of the vehicle angular velocity vector with respect to inertial space, along the body axes corresponding to roll, pitch and yaw, respectively.	rad/sec
$\dot{p}$, $\dot{q}$, $\dot{r}$	Scalar components of the vehicle angular acceleration vector with respect to inertial space, along the body axes.	rad/sec^2
L, M, N	Components of the total external torque on the vehicle about the body axes.	lb-ft
Subscript "c"	Indicates a variable commanded by the astronaut (i.e., p_c = commanded roll rate).	
ϕ, θ, ψ	A set of Euler angles.	radians or degrees
$\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$	Corresponding Euler angular rates.	rad/sec or deg/sec
rms or RMS	Root mean square error.	
n	Number of observations per cell.	
Subscript "e"	Indicates an error quantity.	