ZERO-GRAVITY MANEUVER INSTRUMENTS AND INSTRUMENTATION

B. C. DIXON

Distribution of this document is unlimited

FOREWORD

This study was initiated by the Human Engineering Division, Behavioral Sciences Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio 45433. The work was performed by Lear Siegler Service, Inc., Harrisburg, Pennsylvania 17112, under Contract No. AF 33(657)-11107. MSgt C. W. Sears of the Crew Stations Branch was the contract monitor for the Behavioral Sciences Laboratory. The work was performed in support of Project 7184, "Human Performance in Advanced Systems," Task 718405, "Design Criteria for Crew Stations in Advanced Systems." The work sponsored by this contract was started in April 1963 and completed in April 1964.

Special acknowledgment is made to Major J. C. Simons, MSgt C. W. Sears, and SSgt E. P. Bunch for their invaluable support, both moral and material, during flight tests and instrumentation of the C-131B, and to the personnel of Lear Siegler Service, Inc., for their technical aid.

This technical report has been reviewed and is approved.

WALTER F. GRETHER, PhD
Technical Director
Behavioral Sciences Laboratory
Aerospace Medical Research Laboratories

ABSTRACT

The type ARU-2B/A Attitude Director Indicator (ADI) system was evaluated as a pilot aid in flying a JC-131B aircraft on a ballistic trajectory to produce a zero- or reduced-gravity field. To provide an unburdened display to the pilot, all information necessary to fly a complete zero-G maneuver was presented on the ADI, except airspeed. A Parabola Control Panel was designed to provide six modes of presenting normal acceleration data to the ADI; i.e., zero-G, sub-G, super-G, decay, float, and program modes. The modes were effective, except for the float and program modes which are still experimental. Data from 385 maneuvers at various gravity levels from 0 G to 0.75 G revealed that when flying gravity levels below 0.25 G an accuracy of ±0.05 G could be maintained. This is generally considered an acceptable parabola. However, when flying gravity levels greater than 0.25 G the errors became greater than +0.05G. As the desired gravity level is increased, the parabola time is increased and a high degree of accuracy is more difficult to maintain. In addition, the system errors were greater at the higher gravity levels. These two facts account for most of the errors at increased sub-gravity levels. The ARU-2B ADI system proved to be an effective aid in flying various sub-G, super-G, zero-G, and decay maneuvers.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

SECTION I
INTRODUCTION

A. Pre-accelerometer Instrumentation

In 1958, the need for various studies of human and equipment behavior in a zero-gravity environment was realized. At that time, a method of simulating a zero-gravity field was initiated by flying an airplane on a ballistic trajectory and a JC-131B type airplane was used for the initial studies. Various types of display systems were used to display acceleration information to the pilot for flying the maneuver. One of the very first indicators was the pilot's wallet. The wallet was placed on the instrument panel glare shield before starting the maneuver. Upon entering a zero-gravity field, the wallet would begin to float. In this manner, the floating wallet served as a zero-gravity indicator.

A second method employed a golf ball suspended between two rubber bands. As the golf ball floated to allow the rubber bands to assume a horizontal position, the aircraft was at zero gravity. This display was supplemented with a mechanical G-meter.

Still another method utilized a round cork in a clear plastic sphere. As the pilot flew the aircraft at zero gravity, the cork would remain in the center of the sphere.

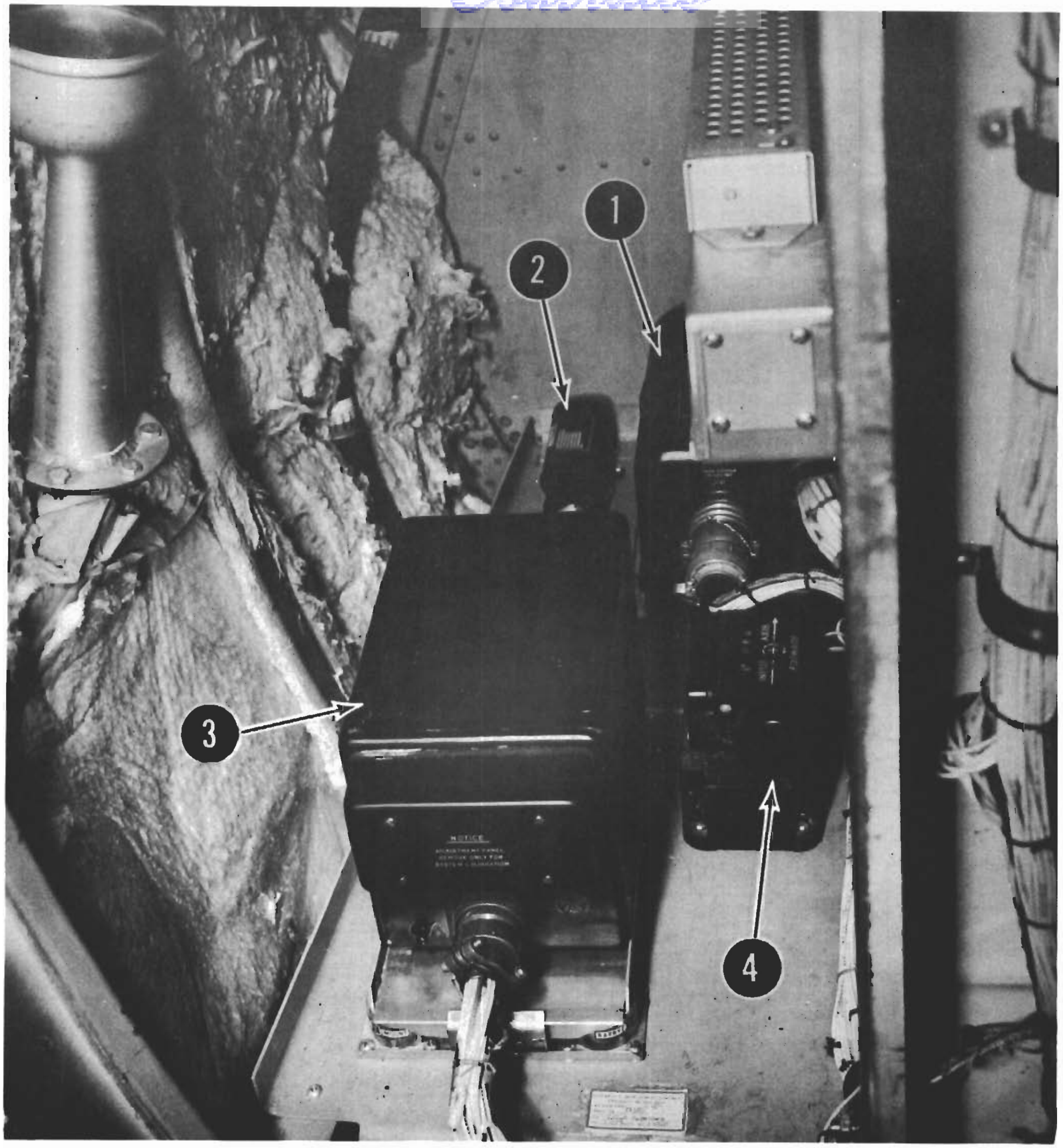
B. Three-Axis Readout

As the program progressed, the need for more accurate display systems to aid the pilot in producing a more precise and longer zero-gravity field became apparent. The emphasis was switched to an accelerometer-based display for zero-gravity flying. The first such system was a three-axis accelerometer readout system. Basically, the system consisted of three B & F Instruments, Inc., Model LF5-20-350 linear strain gage accelerometers as sensors. The accelerometer signals were amplified by Doelcam Model ZHMA-2 DC amplifiers and displayed on Weston Model 699 Microammeters. The meter sensitivity could be switched from ± 3G full scale to ± 0.3G full scale to provide a more sensitive display at zero gravity and still provide information for the 2.5G entry and exit phases of the maneuver.

As the requirements for greater accuracy, increased duration, and various types of maneuvers other than straight zero gravity became necessary, a contract was initiated by the Behavioral Sciences Laboratory of Aerospace Medical Research Laboratories at WPAFB to study the problem, and to design and fabricate a system to provide accuracy within $\pm$ 0.005G maximum error. Other requirements were a longer free-float time, and the capability of sub-G, super-G and decay-type maneuvers. The contract engineer was supplied by Lear Siegler Service, Inc., and work was started in August 1961.

C. Integrated Zero-G Display

Emphasis was placed on an unburdened pilots display to eliminate switching from one indicator to another during different phases of the zero-gravity maneuver. Therefore, a standard AF Type ARU-2B/A Attitude Director Indicator (ADI) was used to display all information to the pilot for both the vertical and lateral axes during the complete maneuver. The components used in this integrated display to drive the indicator are shown in Figure 1.



1. MD-1 VERTICAL GYROSCOPE
2. MC-1 RATE SWITCH
3. CPU-4/A FLIGHT DIRECTOR COMPUTER
4. TRU-2/A RATE OF TURN TRANSMITTER

Figure 1

ADI SYSTEM COMPONENTS MOUNTED IN JC-131B AIRCRAFT

As an interim means of providing a sub gravity display, a G-level selector and isolation amplifier was designed and fabricated. This system was installed and used in aircraft C-131B 53-7823. Figure 2 is a block diagram of the complete integrated display, with the accelerometers and G-level selector in the circuit, as used in the first zero-gravity airplane. With the use of this display, the pilot could fly a complete maneuver and have all information displayed on two instruments, the Airspeed Indicator and the Attitude Director Indicator.

Looking at Figures 3 and 4, a typical parabola is flown in the following manner: During level flight prior to starting a maneuver the ADI appears as shown in Figure 3, except the horizontal director needle is full scale down indicating more than 0.2G, the displacement pointer is down almost half scale, indicating 1G on a 2.5G full scale displacement, and the warning flags are out of sight. To start the maneuver, power is increased to 42 inches Hg, 2400 RPM, by the co-pilot, and the aircraft is placed in a 10-degree dive. The pitch attitude change is displayed to the pilot on the sphere of the ADI. When the airspeed reaches 250 knots indicated, the pilot

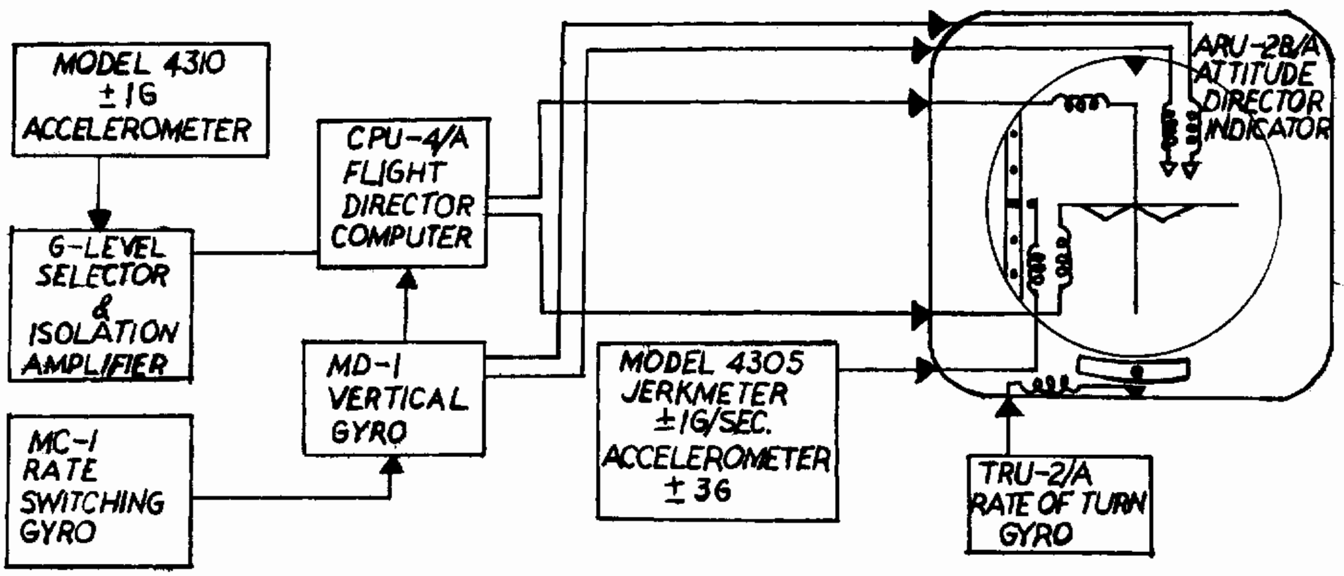
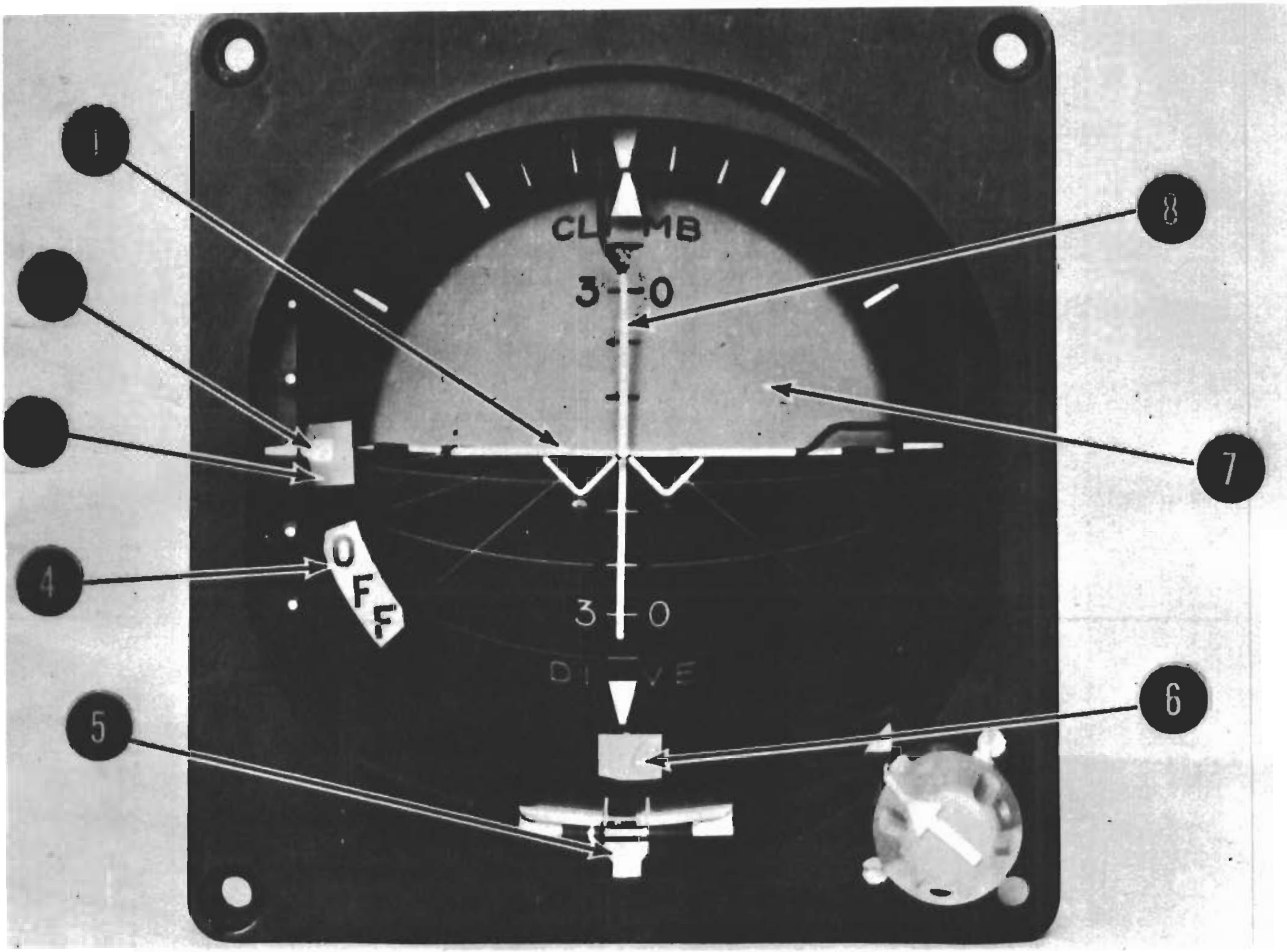


Figure 2

ATTITUDE DIRECTOR DISPLAY SYSTEM WITH
G-LEVEL SELECTOR & ISOLATION AMPLIFIER



1. HORIZONTAL DIRECTOR NEEDLE
2. DISPLACEMENT POINTER (BUG)
3. GLIDE SLOPE FLAG
4. POWER FLAG
5. RATE OF TURN NEEDLE
6. LOCALIZER FLAG
7. SPHERE
8. VERTICAL DISPLACEMENT POINTER

Figure 3

TYPE ARU-2B/A ATTITUDE DIRECTOR INDICATOR

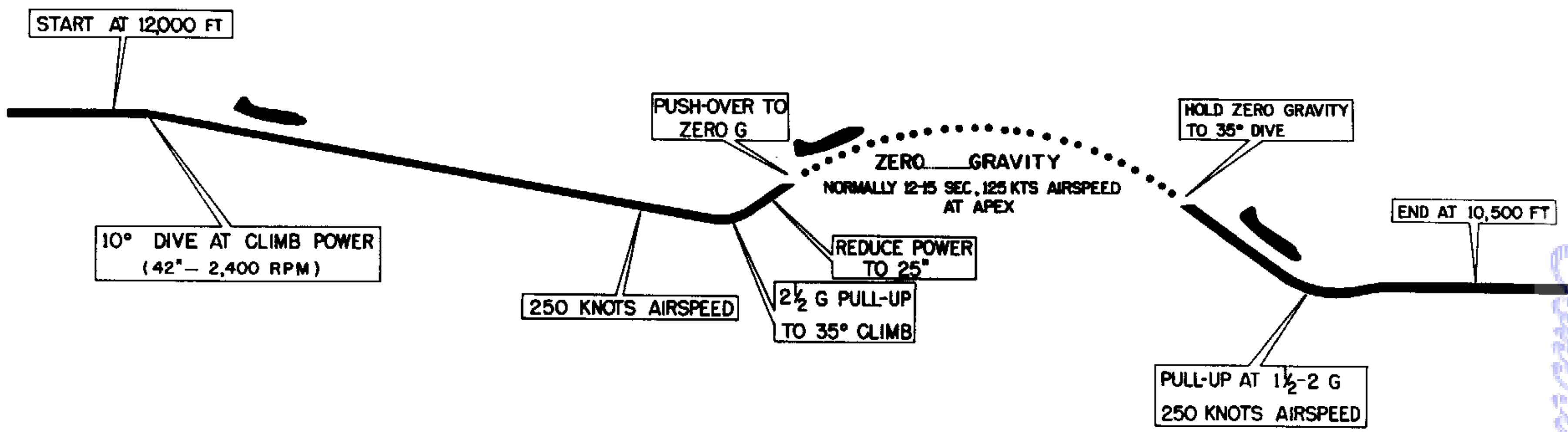


Figure 4

ZERO-GRAVITY-MANEUVER PROFILE

controls the airplane into a 2.5G climb. During this phase, the displacement pointer on the ADI moves down full scale to indicate 2.5G and the changing pitch attitude is displayed on the sphere of the ADI. The co-pilot reduces power to 25 inches Hg during the pull-up phase. When the aircraft reaches 35 degrees nose up, the pilot pushes the stick forward and the displacement pointer begins to move up toward center to indicate the aircraft is approaching zero gravity. When 0.2G is reached, the horizontal director needle begins moving toward center to provide a more sensitive display during the actual zero-gravity phase of the maneuver. The horizontal director needle is scaled for 0.2G for 2.22 Centimeters (7/8 inch) which is full displacement from center. The pilot controls the pitch axis of the airplane to maintain zero-G by keeping the horizontal director needle centered until the aircraft reaches a 35-degree nose-down attitude at which time the pullout phase is executed back to level flight. During the pullout, the displacement pointer displays the 2.5G maximum for this phase of the maneuver. In addition to the above information, roll attitude is displayed on the sphere and a more sensitive roll attitude on the vertical director needle which is scaled for 12 degrees left or right roll for full needle displacement. A needle and ball display at the bottom of the indicator provides a turn rate and slip indicator. In this manner, there is enough information displayed on one indicator (excluding airspeed) to fly a complete parabola, providing a nonsensitive display for the entry and pullout phases and an extremely sensitive display for the zero-gravity phase of the maneuver. With the addition of the G-level selector, a reference voltage was established and compared to a $\pm$ 1G accelerometer output to provide an error signal for the pilot to fly to maintain a preselected gravity level. This information was then displayed on the horizontal director needle of the ADI during the zero or subgravity phase of the maneuver.

SECTION II
PARABOLA CONTROL PANEL

A. General Description (see figs. 5 thru 9)

During the time the previously explained equipment was being used, an experimental display system was being designed and fabricated under the direction of Aerospace Medical Research Laboratories. When the JC-131B 53-7823 aircraft was retired from zero-gravity flying and the JC-131B 53-7806 aircraft was modified for zero-gravity work, a Parabola Control Panel was installed along with the integrated flight display and 3G accelerometer/jerkmeter. The parabola control panel was designed as experimental equipment to study various modes and methods to present information to the pilot for zero-, sub-, and super-gravity flying in the JC-131B aircraft.

A Donner Model 4305 Accelerometer/Jerkmeter is the sensing element attached to the aircraft on a rigid mount in the center of the float compartment under the floor. The accelerometer will measure 3G maximum and the sensitivity of the jerkmeter is 1G/second. The basic circuit to develop an error signal is in block diagram form in Figure 8. Signals from the 3G accelerometer are input to the inverter amplifier in the parabola control panel at 2.5 volt/G. The output of the inverter amplifier is used to drive the displacement pointer of the Attitude Director Indicator which is scaled for ± 2.5G full deflection. This information is used during the 2.5G entry and pullout phase of the maneuver. The output of the inverter amplifier is also fed to the summing amplifier where it is summed with the output of the jerkmeter and a bias voltage from one of the various bias generators. The output of the summing amplifier is an error signal resulting from acceleration, jerk (acceleration rate) and a bias signal. The signal is input to the CPU-4/A Flight Director Computer which drives the horizontal director needle of the Attitude Director Indicator. The sensitivity is ± 0.2G for full scale deflection which is ± 2.22 Centimeters (7/8 inch). This is the sensitive display provided during the zero or sub-G phase of the maneuver. The bias voltages input to the summing amplifier are derived from the bias generators. Any mode may be selected as a bias source by turning the mode selector switch on the front of the parabola control panel. The modes available are Zero-G, Sub-G, Super-G, Decay, Program, and Float.

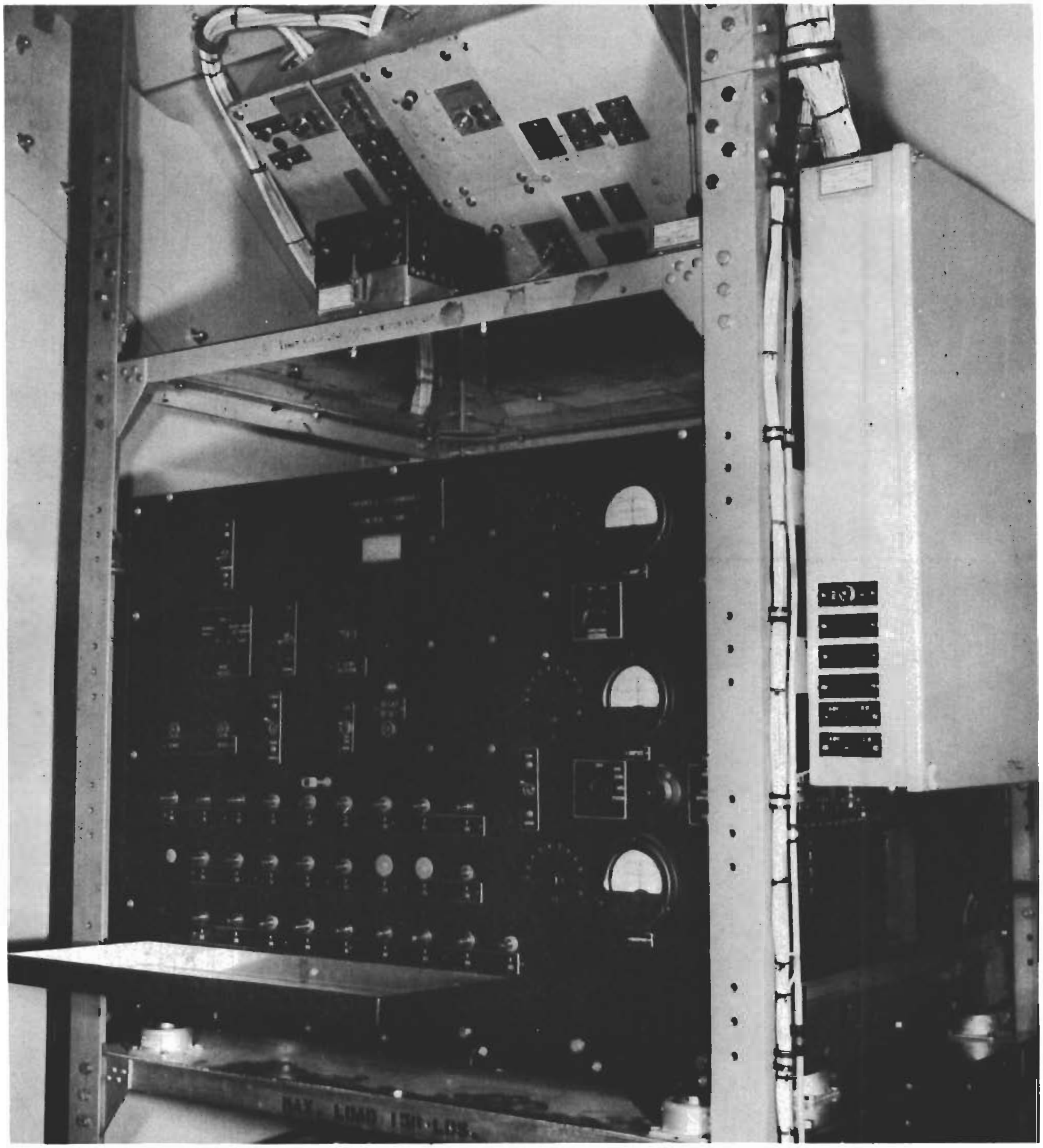


Figure 5

FRONT VIEW PARABOLA CONTROL
PANEL MOUNTED IN JC-131B AIRCRAFT

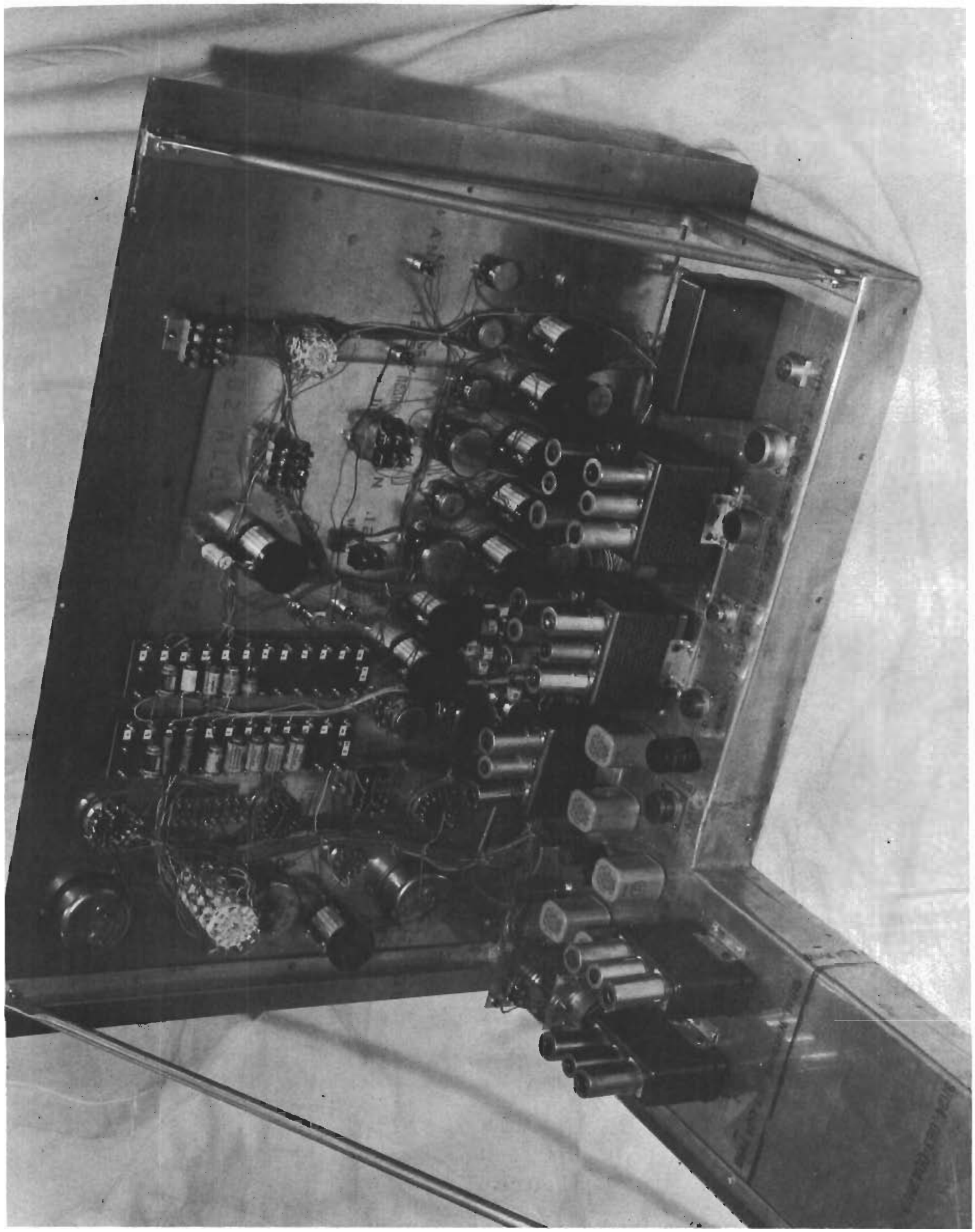


Figure 6

REAR VIEW PARABOLA CONTROL PANEL

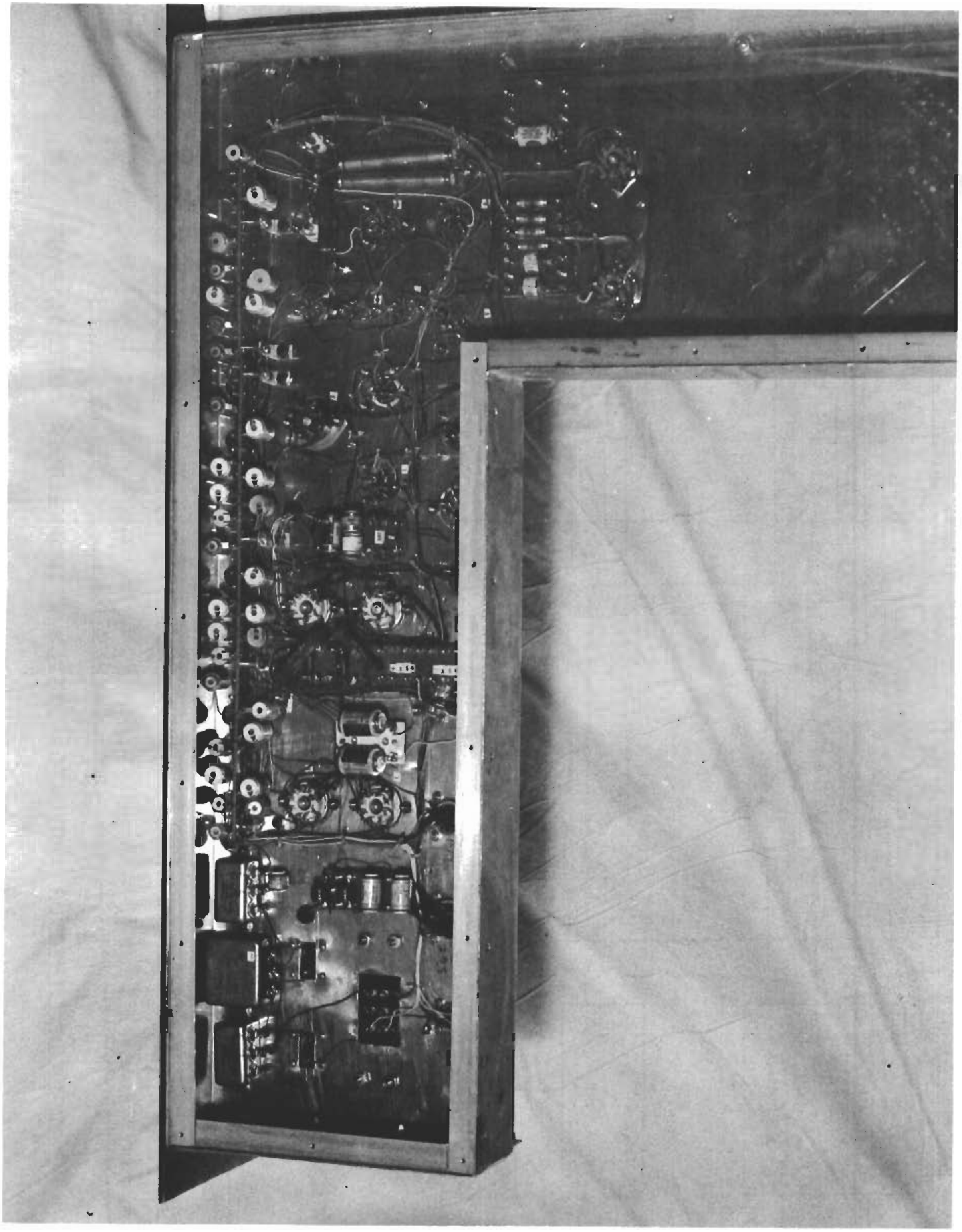


Figure 7

BOTTOM VIEW PARABOLA CONTROL PANEL

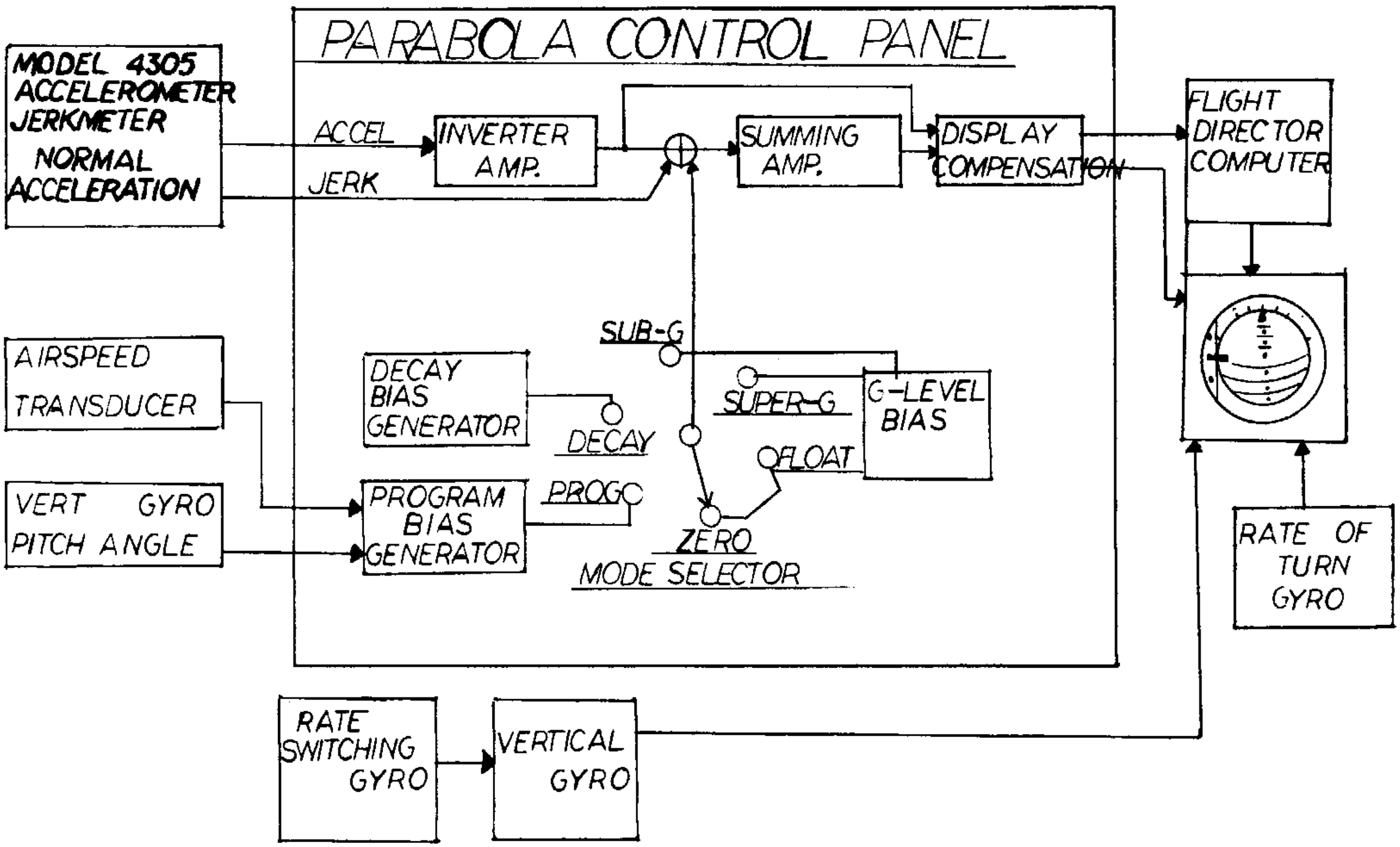


Figure 8

ATTITUDE DIRECTOR INDICATOR SYSTEM WITH PARABOLA CONTROL PANEL

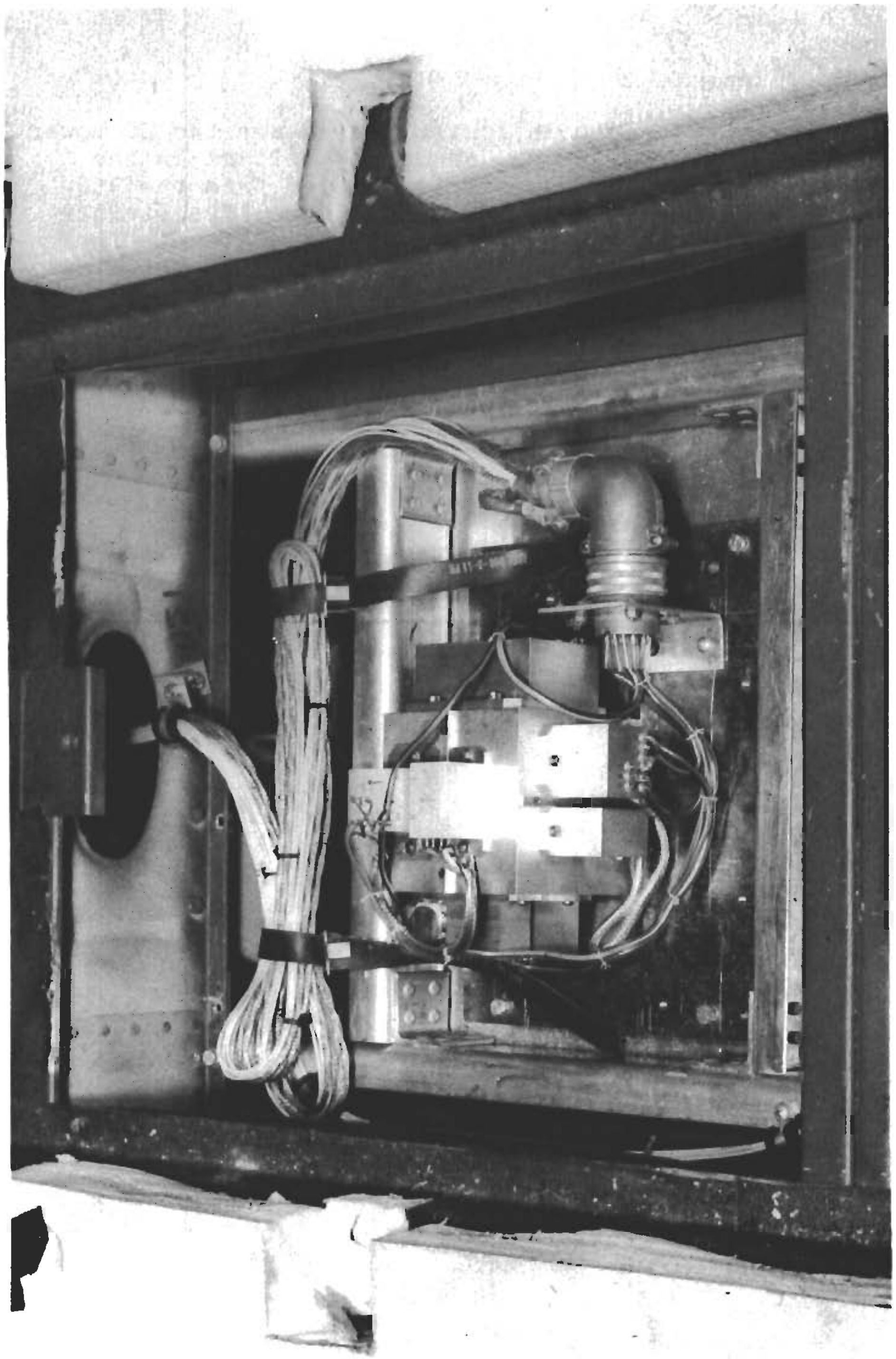


Figure 9

3 AXIS ACCELEROMETER PACKAGE

B. Power Supplies (see figs. 10 thru 13)

Provided with the parabola control panel are two DC power supplies. ± 350 VDC is used as supply voltage in the amplifiers. A ± 10 VDC supply is derived from the 350-volt supply by inputting ± 350 VDC to a voltage divider circuit with 10-volt zener diodes for regulation. The 10-volt power is used throughout the system as the simulation voltages, bias voltage and amplifier balance supply. Due to this, any drift in power supply will be reflected in the accuracy of the equipment. An analysis of the 350-volt power supply revealed the following facts:

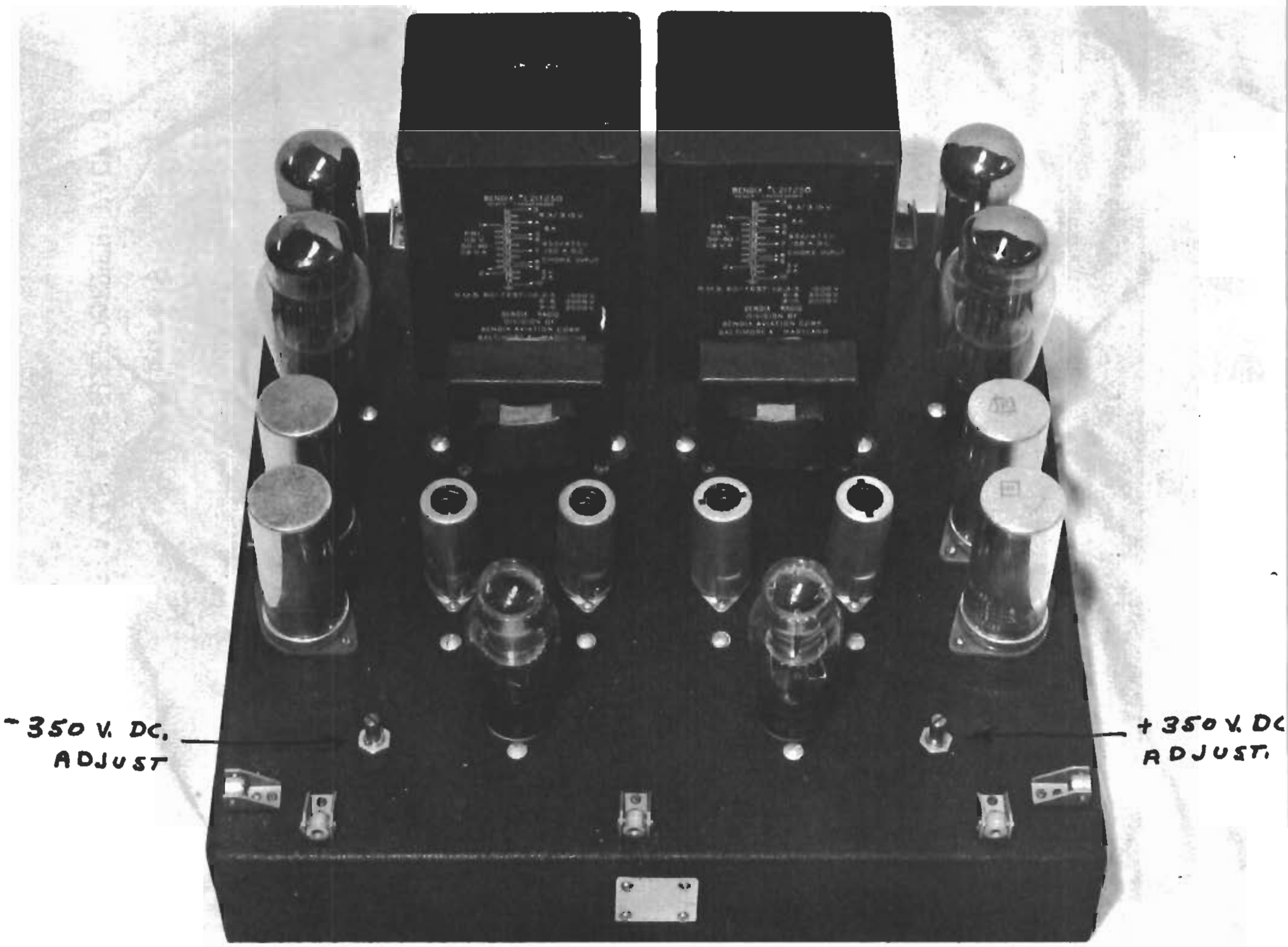


Figure 10

350 VDC POWER SUPPLY

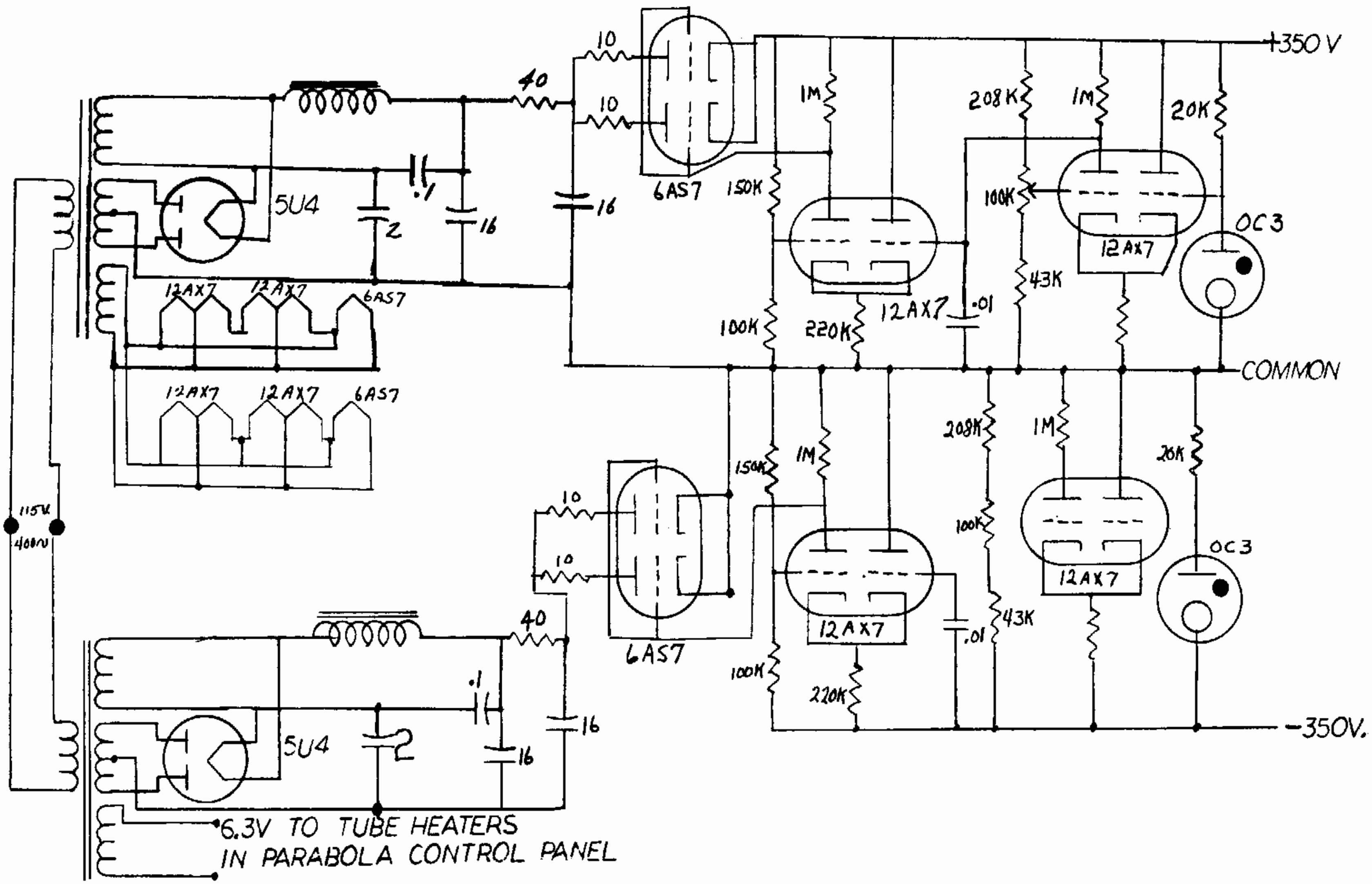


Figure 11

350 VDC POWER SUPPLY SCHEMATIC

Regulation of the Power supply is marginal up to 300 ma and is intolerable above a 300-ma load. At 300 ma, regulation of the positive power supply is 0.36% and regulation of the negative supply is 0.68%. With a 325-ma load, regulation of the positive power is 3.2% and regulation of the negative supply is 1%.

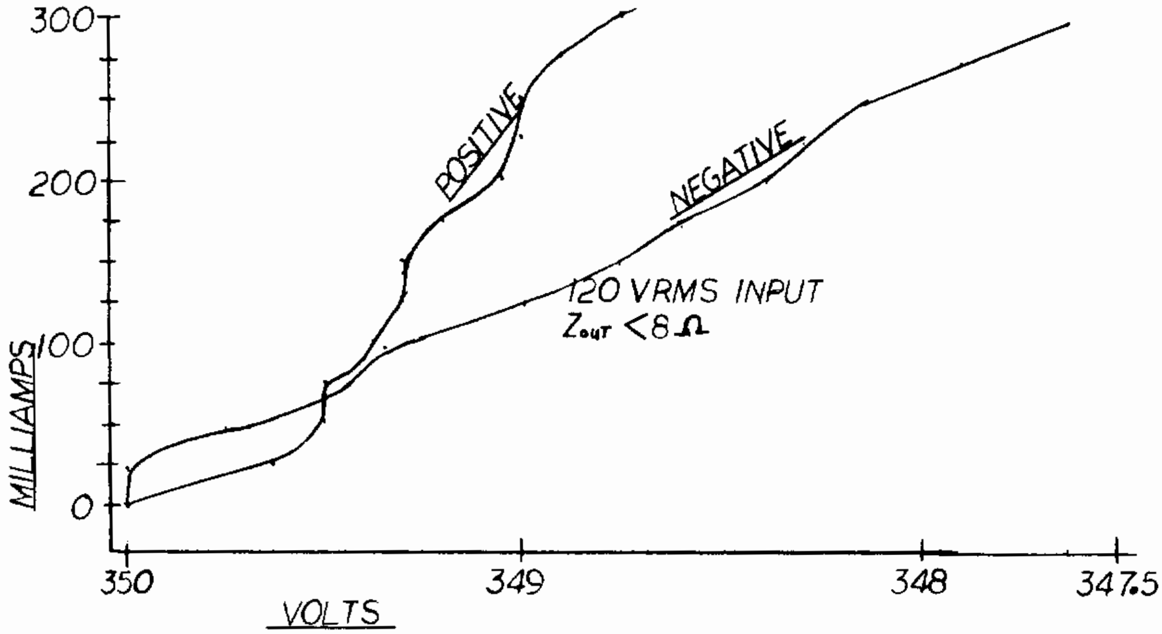


Figure 12

350 VDC vs. LOAD

A more stable 24 VDC regulated power supply is used for bias voltages to the programmer and excitation to the airspeed transducer. The 24 volt supply is used only with the program mode. Both power supplies require a 115-V, 400-cycle power input from the main aircraft inverter. Power input is controlled by the power switch on the parabola control panel. Vacuum tube failures were the only problems experienced with the power supplies during 10 months' operation.

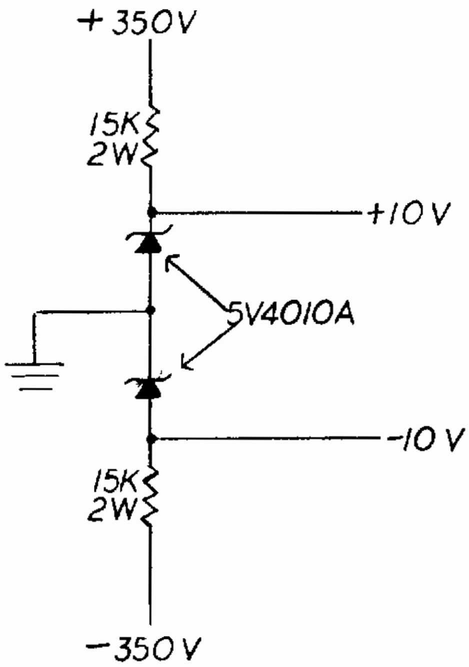


Figure 13

± 10 VDC VOLTAGE DIVIDER CIRCUIT

C. Meters

Looking at Figure 5, the reader will see three meters and the respective switches on the front of the parabola control panel. The top meter labeled AMP is to check amplifier centering. When the amplifier centering switch is turned ON, the input to each amplifier is grounded and the output is fed through the amplifier centering switch to the AMP meter selector switch. Using the AMP meter selector switch, each individual amplifier output can be read on the AMP meter and the amplifier centering adjusted. The INPUT meter is used to check all power supply voltages and simulated input signals. The OUTPUT meter is used to monitor various output voltages such as the output of the inverter and summing amplifiers, the programmer output, G-level selector potentiometer and the vertical gyro pitch centering.

D. Simulation (see fig. 14)

The capability of simulating any input signal to the parabola control panel is provided for ground testing purposes and making "in flight" adjustments. To simulate a signal, it is necessary to have the SYST-SIM switch in the SIM position and the signal simulator selector to the desired signal. With the INPUT meter selector switch at position 2, the simulated signal will be displayed on the INPUT meter.

E. Mode Selector

Each of the six modes may be selected by rotating the mode selector switch. For every mode except Float, the inverter and summing amplifiers are operated as voltage amplifiers. The difference in each mode is the method used to develop a bias signal to sum with the accelerometer signal into the summing amplifier. Each method of developing a bias will be considered separately along with problems encountered and solutions to the problems.

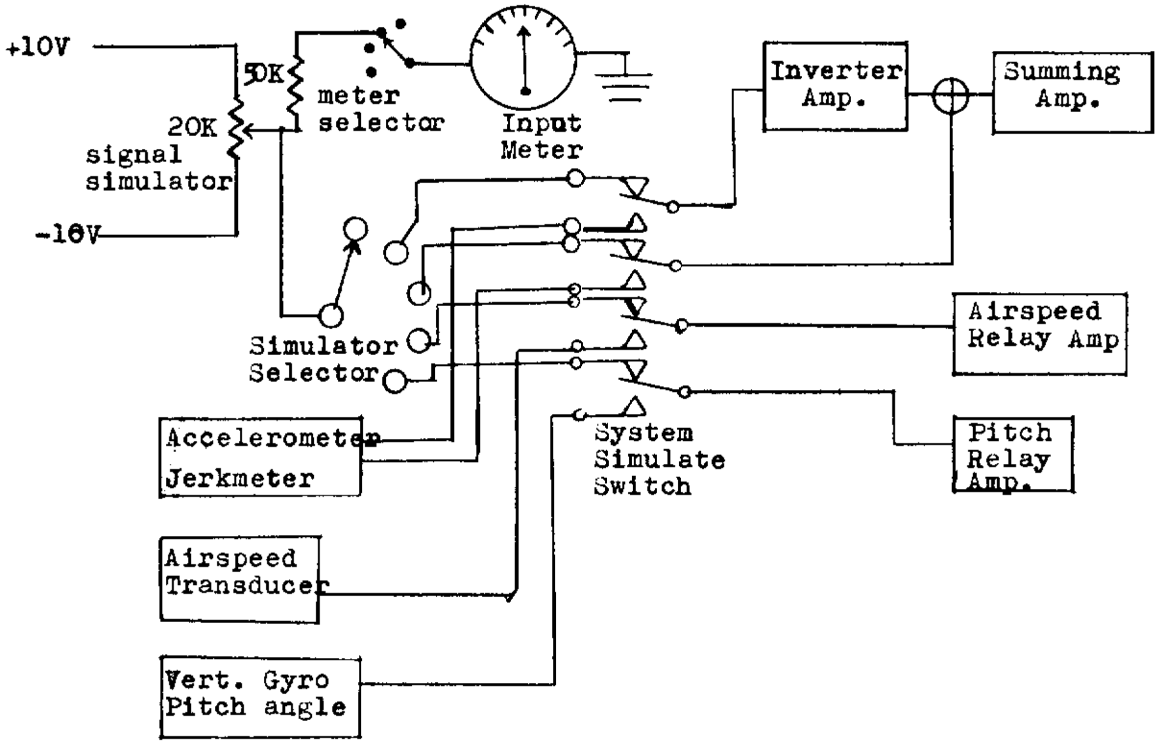


Figure 14

SIMULATOR CIRCUIT

F. Zero-G Mode (figs. 15, 16, 17)

When the mode selector is placed in zero-G position, the bias input to the summing amplifier is 0 volts. When the aircraft reaches zero gravity, the accelerometer output is 0 volts which results in a 0 output from the summing amplifier. This drives the horizontal director needle on the Attitude Director Indicator to center. To maintain zero gravity, the pilot must make the necessary pitch corrections to keep the horizontal director needle centered.

Two major problems have been encountered flying the zero-G mode: The DC operational amplifiers drift more than can be tolerated, making it necessary to check the amplifier centering after every two or three maneuvers. If a slight amount of drift occurs in either the inverter or summing

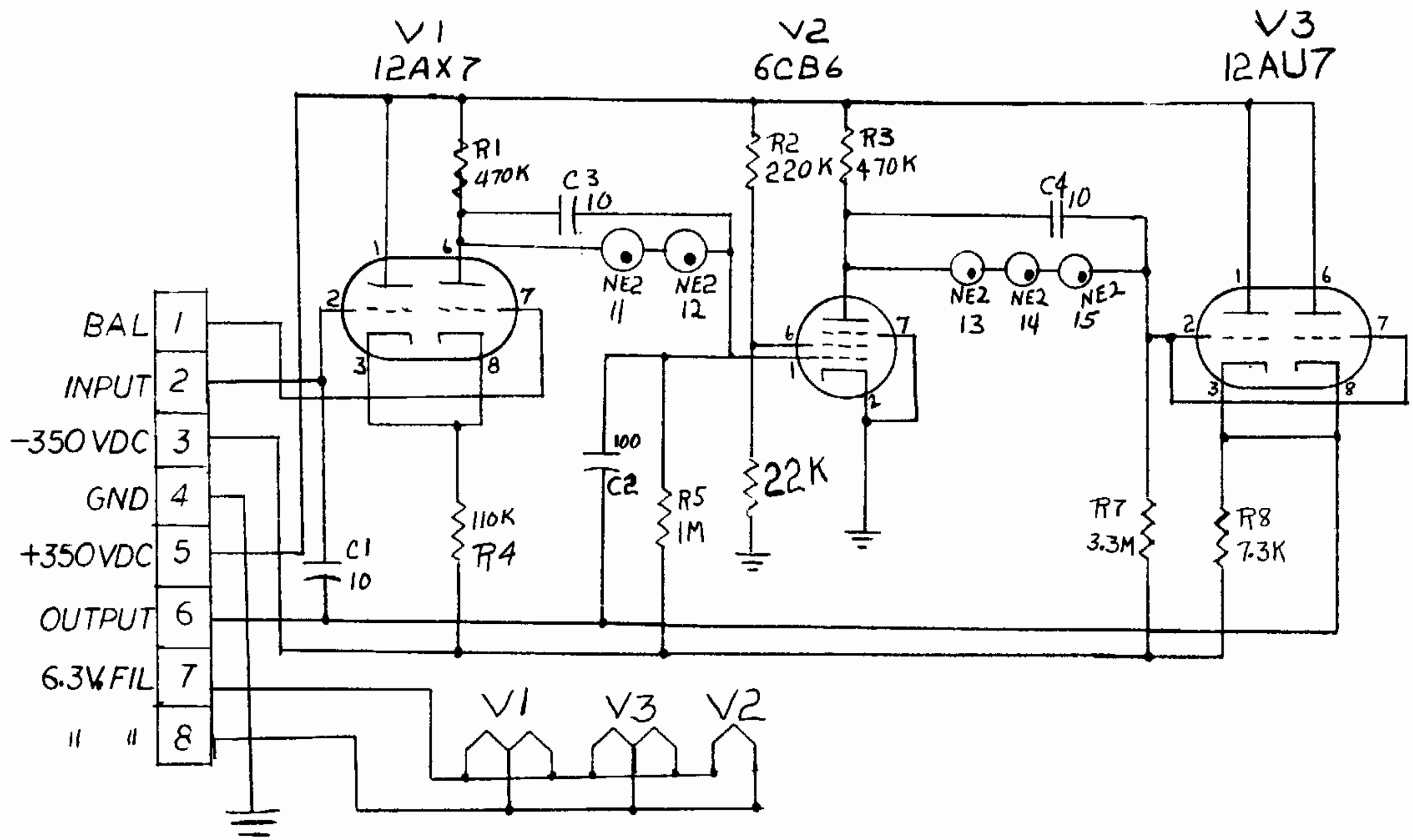


Figure 15

OPERATIONAL AMPLIFIER SCHEMATIC

Figure 16

OPERATIONAL AMPLIFIER

amplifier, an erroneous signal is introduced resulting in a gravity level other than zero when the horizontal director needle is centered. The Amplifiers are Dynalyzer Operational Amplifier Model 2, manufactured by Dynamic Analysis Company. They are stabilized by neon tubes which are not suitable for this use. To minimize this problem, personnel responsible for in-flight operation of the parabola control panel, check amplifier centering at frequent intervals and make necessary corrections.

The second problem encountered during zero-G mode was instrument parallax error. This error would vary depending on pilot height and seat position. To eliminate the problem, a parallax correction adjustment was added to the display compensation circuit. This adjustment will move the horizontal director needle ± 0.64 Centimeter (1/4 inch) from center which has been sufficient to correct for any parallax error encountered. Without the parallax adjustment, it could be possible to have up to a 0.05G error for a 0.64 Centimeter error on the horizontal director needle. The amplifier drift and parallax error problems are common to all modes.

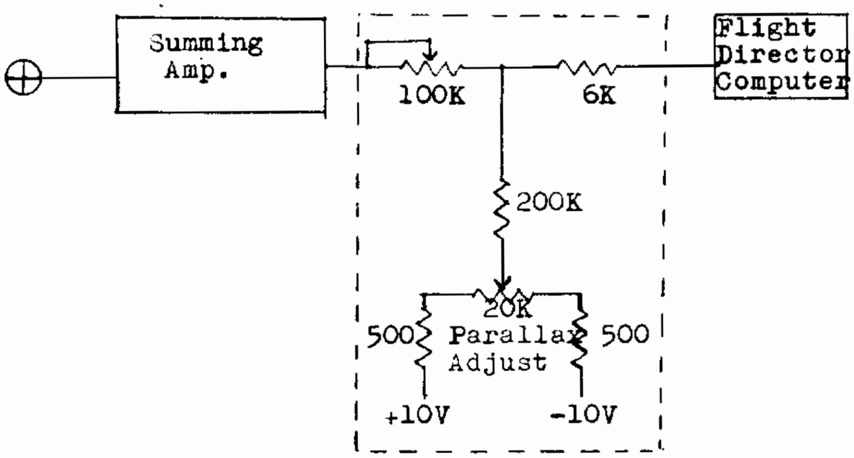


Figure 17

DISPLAY COMPENSATION CIRCUIT FOR
HORIZONTAL DIRECTOR NEEDLE

G. Select Sub-G Mode

When the mode select switch is placed in the select sub-G mode, the bias voltage input to the summing amplifier is selected by adjusting the G-level selector potentiometer. In order to select a 0.1G maneuver, the G-level selector would be set for 0.25 volt input to the summing amplifier. When the aircraft reaches 0.1G, the accelerometer input to the summing amplifier is + 0.25 volt resulting in 0 volt output from the summing amplifier which drives the horizontal director needle to center. The 0.1 gravity level will be maintained as long as the horizontal director needle is kept centered. Any gravity level from 0-G to +2G may be selected with the G-level selector. In addition to the drift and parallax error problems, nonlinearity and scaling of the panel meters present a problem. The meters are Telectro Industries Corporation, Model 331 microammeter. The mechanical centering adjustment is sealed inside the meter making it impractical to attempt power off centering adjustments. The meters are scaled to read gravity levels up to ± 2G. Between 0 and full scale, there are 20 divisions, each equal to 0.1G. This scaling coupled with the size of the meter made it very difficult to set an accurate fractional gravity level into the system. The input meter is nonlinear which introduces an error when the higher subgravity levels are set. This problem has been minimized by making the meters more sensitive. Each division on the meter equals 0.05G which makes a more accurate G-level adjustment possible.

H. Select Super-G Mode (fig. 18)

In order to maintain a super gravity level (above 1G), the airplane is flown in a bank to maintain the desired gravity level. This bank angle is determined by:

$$n = \frac{1}{\cos \phi}$$

where n = gravity level

ϕ = bank angle

When the mode selector is moved to the select super-G position, the output of the summing amplifier is switched from the horizontal director needle to the vertical director needle, because the airplane will be controlled in the roll axis instead of the pitch axis to maintain the super gravity level, and the vertical director needle is the more normal display for the roll axis control. The desired gravity level is set on the G-level selector in the same manner as for the sub-G mode. In order to aid the pilot to maintain a G-level requiring up to 60 degrees bank, the E-4 autopilot was modified to allow up to a 60 degree bank using the turn knob on the autopilot flight controller. A switch was installed to change from normal autopilot to high bank angle capability.

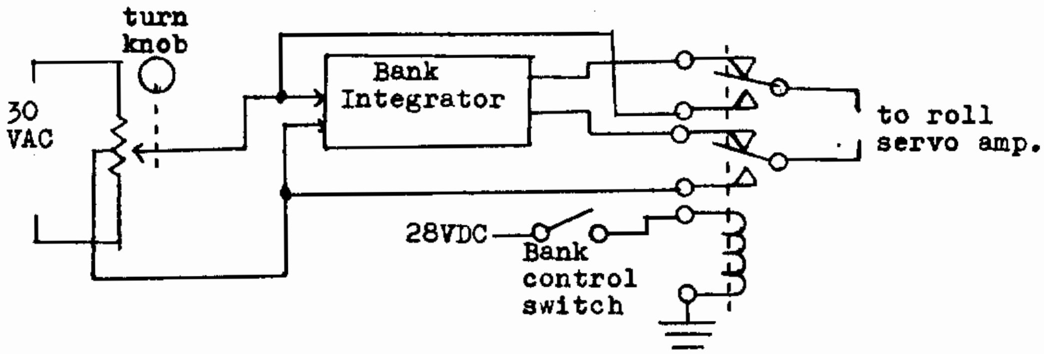


Figure 18

E-4 AUTOPILOT MODIFICATION FOR HIGH BANK ANGLES

I. Decay Mode (figs. 19, 20)

When the mode selector is moved to the decay position, all bias input signals to the summing amplifier are from the decay bias generator. The original decay bias generator provided a constant rate decay from a pre-selected gravity level to another pre-selected gravity level. This circuit provided a linear decay presentation, however all the desired features for a decay were not available. The two most desirable were the capability of a selectable decay rate and to decay in either direction. That is from a lower gravity level to a high one or vice versa. Another problem encountered with the decay circuit was the complex adjustment and operation procedure. To fly the decay

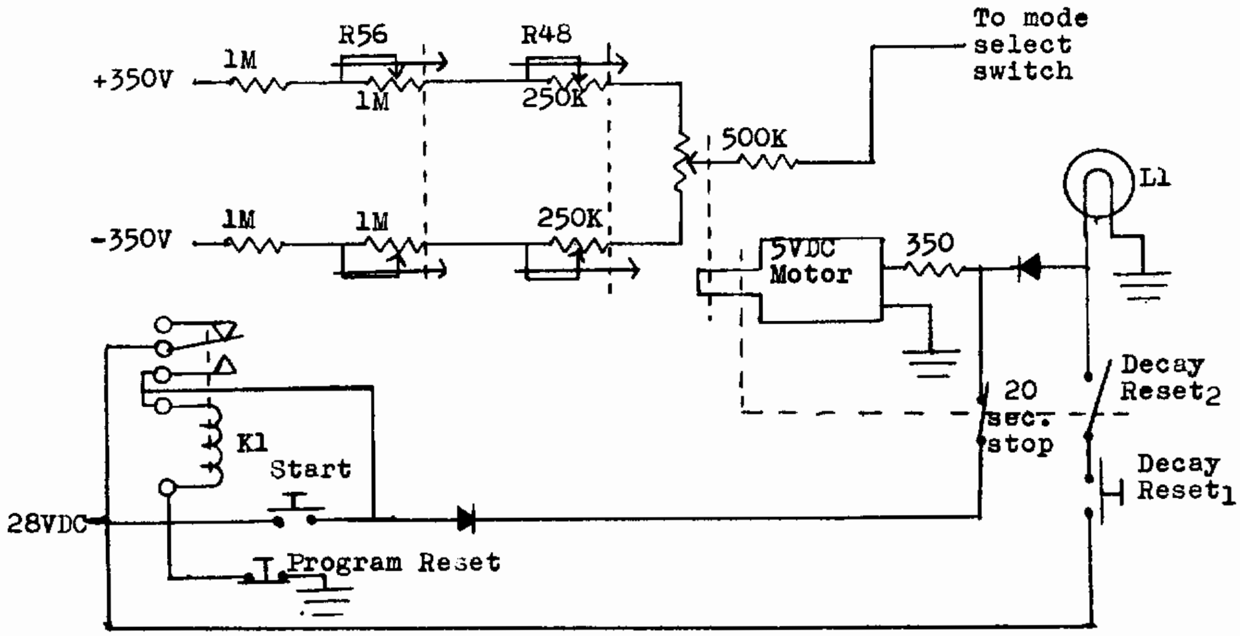


Figure 19

FIRST DECAY GENERATOR

maneuver using this circuit, it is first necessary to set the desired gravity levels using R-56 and R-48 variable resistors. When the initial gravity level is reached, the start button is closed momentarily which starts the motor M-1 running to drive the 50K pot and to execute the decay presentation to the pilot by changing the bias input to the summing amplifier. As the pilot keeps the horizontal director needle centered, the gravity level of the aircraft changes. The motor continues to run after the start switch is released, receiving 28 VDC through the contacts of K1 until the 20-second stop switch opens. At this time, decay reset 2 closes. After each maneuver, it is necessary to de-energize K1 by momentarily opening the program reset switch. To reset the 50K motor driven pot to its original position, decay reset 1 is held closed manually until L1 goes out indicating decay reset 2 has opened and the 20-second stop switch has closed. The decay generator is then ready for another maneuver. A new decay circuit was installed which provides an exponential decay, has the previously mentioned desired features, and is more simple to operate. The new decay circuit is an RC delay with the capability of switching in different value capacitors to provide a selected rate of decay. When flying the decay maneuver using this circuit, it is first necessary to dial in the desired sub-G level on the G-level selector and the desired decay rate on the decay rate switch. If the maneuver is to decay from a sub gravity level to zero gravity, then the sub-zero switch should be in the sub position to start - and when that gravity level is reached, flip the switch to zero position and the decay presentation will begin by changing the input bias to the summing amplifier. A linear decay could be achieved by using an electronic integrator circuit, however the exponential decay has proven satisfactory. To prepare for the next maneuver, it is necessary only to move the sub-zero switch back to the original position. If it is desired to decay from zero gravity to a higher gravity level, start the maneuver with the sub-zero switch in the zero position and move to the sub position when the aircraft reaches 0-G.

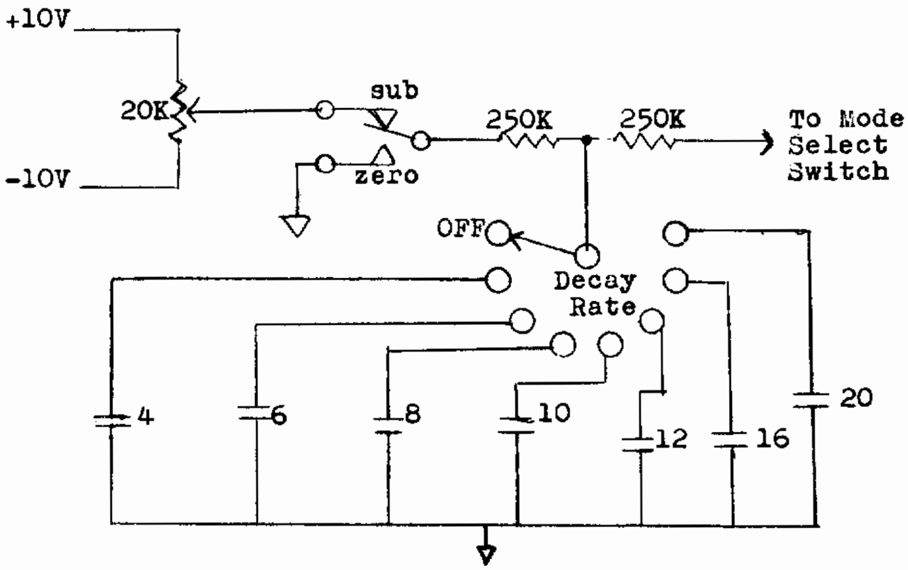


Figure 20

NEW DECAY CIRCUIT

J. **Float Mode** (fig. 21)

When the mode selector is in the float position, a zero-gravity bias is input to the summing amplifier. The float mode is designed to be used to free float capsules. When the zero gravity level is reached, the capsule is released to float and a switch is actuated which changes the inverter and summing amplifiers to integrators.

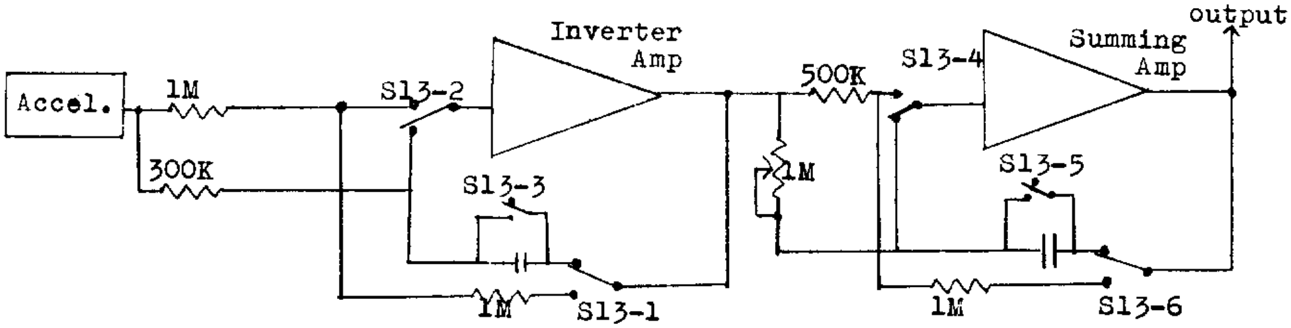


Figure 21

INVERTER AND SUMMING AMPLIFIERS AS INTEGRATORS

If the integrate switch S-13 is switched to the integrate position at the instant the capsule is released, the inverter amplifier integrates the acceleration error which results in a capsule rate error. The summing amplifier integrates the rate error which results in a capsule position error. This is displayed to the pilot on the horizontal director needle. During flight tests of the float mode, the movement of the horizontal director needle was much too rapid for the airplane to follow. A maneuver was required by which the capsule would be returned to its original release point, but has proven to be impractical. The circuit has been changed to allow only the summing amplifier to integrate when S-13 is placed in the integrate position. The output of the summing amplifier now becomes a rate signal which requires only enough aircraft control to stop the capsule from moving instead of the more violent maneuver required to return it to the original release position. This configuration has not been flight tested as yet and the float mode is still experimental.

K. Program Mode (fig. 22)

The program mode is designed to provide the proper bias input to the summing amplifier for each phase of the maneuver. The bias voltages are automatically switched by relays sequentially energized by signals originating from an airspeed transducer and a vertical gyro. The bias voltages are supplied by a voltage divider circuit energized by the 24 VDC regulated power supply.

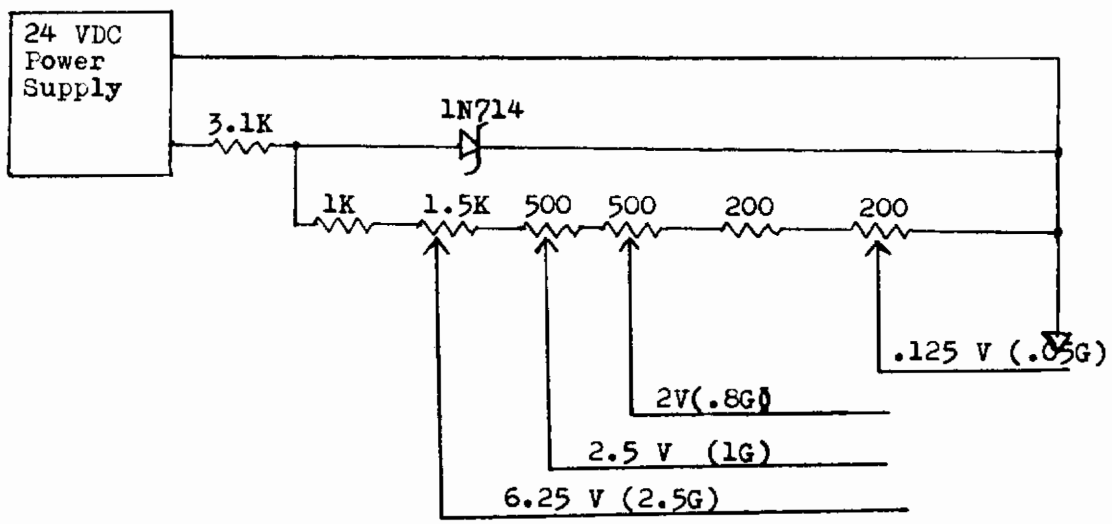


Figure 22

VOLTAGE DIVIDER

A schematic of the program bias generator appears in Figure 23. Relays K1, K2, K3, K4, and K5 are automatically energized to provide the proper bias voltages. To start a maneuver, relay K1 is manually energized by momentarily closing S8. This places a 2V bias at the input of the summing amplifier which calls for a dive at 0.8G. When a pre-selected airspeed is reached, K6 closes and energizes K2 coil which opens the ground to K1 coil and inserts a 6.25 volt bias to display a 2.5G pull up. When a pre-selected pitch-up attitude is reached, K7 closes and energizes K3 which opens the ground to K2 coil and channels a 0 volt bias to the summing amplifier for 0 gravity until a pre-determined pitch-down attitude is reached. At this time, K8 closes which energizes K4 and de-energizes K3 by opening the ground. A 0.25 volt bias is passed to the summing amplifier for a period of 2 seconds. The purpose of this 0.1 gravity level for 2 seconds is to lower floating masses to the floor easily prior to the 2.5G pull out. The 2 second time delay is accomplished by the R82 and C9 RC delay to K9 coil. If S7 is in the single position, K10 and K5 both energize. The ground for K5 is provided through S7 from K10 contacts. When K5 energizes, a 6.25 volt bias is passed to the summing amplifier for a 2.5G pullout to end the maneuver. If S7 is in the cycle position when K9 closes, 28 volt is passed through S7 to K2 coil which closes to start another maneuver inserting a 6.25 volt bias for the 2.5 pull up. Simultaneously, K10 and K5 energize. However, when K5 energizes, the ground to K4, K9 and K10 is opened and when K10 de-energizes, the ground to K5 is opened. This automatically puts all relays in a de-energized position and ready for another maneuver. With S7 in the single position, the programmer is re-set manually by momentarily depressing S9.

Several problems have been encountered with the programmer. On the first flight test of the programmer, two separate problems became apparent immediately. When S8 is momentarily depressed to start the dive phase of the maneuver, a 2-volt bias is input to the summing amplifier which is equal to 0.8G. The desired attitude for this phase is 10 degrees nose down. According to information from analog computer studies, in a 10-degree dive with full climb power, the increasing airspeed would be sufficient to maintain 0.8G. However, in actual flight it was necessary to increase the dive angle beyond 10 degrees to maintain the 0.8 gravity level. When the pre-selected airspeed was reached (240 KIAS), the aircraft was in a 25-degree dive. To eliminate this problem, contact set 4 of K1 was used to switch in gyro reference instead of accelerometer during this phase of the maneuver. Thus, when K1 is energized, gyro reference is switched in and a bias voltage equal to

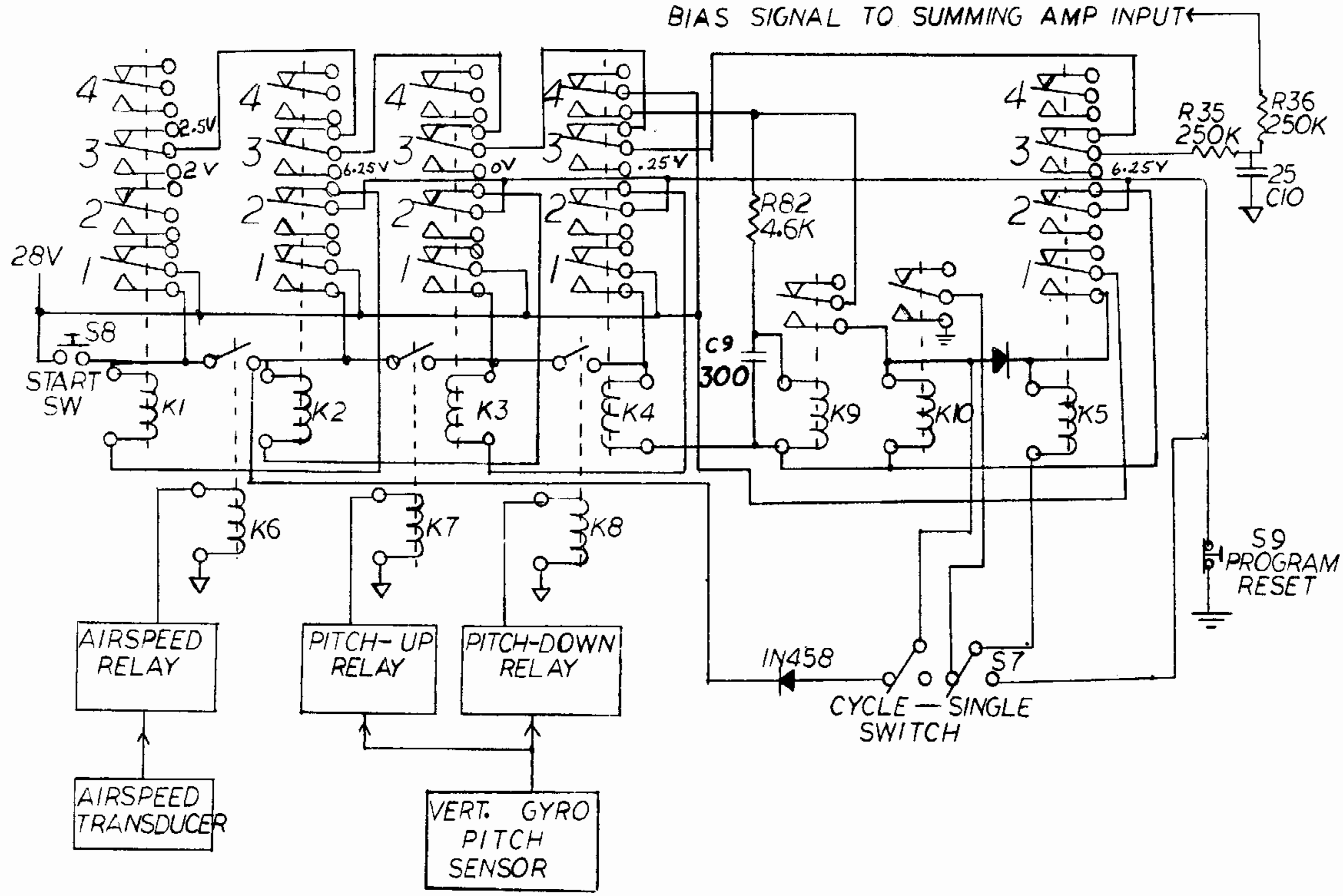


Figure 23

PROGRAM BIAS GENERATOR SCHEMATIC

a 10-degree dive is switched into the summing amplifier. When K2 energizes, the ground to K1 is opened and it de-energizes, placing an accelerometer reference back into the system.

Another problem was that the RC delay, composed of R35, R36 and C10 was much too long. This delay is 12.5 seconds and a check of data for previous non-programmed parabolas revealed that a 3- to 4-second transfer time is more realistic. A rotary switch was installed with the capability of switching different value capacitors in place of C10 to provide a time delay ranging from 2 to 10 seconds. During later flight tests, a 4- to 5-second transition time was found to be most desirable.

The output from the G-level selector has been connected to contact set 3 of K3 in place of the 0-volt-bias input. This was done to provide the capability of performing a subgravity maneuver while on the program mode. The 0.25 volt bias at set 3 of K4 and the 2-second time-delay circuit have been eliminated for two reasons. A normal transition time from 0G to 2.5G of 4 seconds is provided to lower floating objects to the floor easily. The second reason - if a subgravity level greater than 0.1G were being flown, it would be necessary to go to a lower gravity level during the 2 seconds. This would be an undesirable feature.

The program mode is still experimental with several changes to be made. Plans are to tie the output of the summing amplifier to the autopilot to provide a complete fully automatic maneuver. However, problems which have not been resolved at this writing prevent automating this mode.

SECTION III
SYSTEM EVALUATION

A. Data Collection (fig. 24)

Acceleration signals were recorded on a CEC type 5-119,50 channel oscillograph recorder using CEC type 7-315 Galvanometer. Signal sources were from Donner Scientific Corporation Model 4310 ± 1G servo accelerometers.

The area of most concern during a parabola is between termination of the 2.5G entry and beginning of the 2.5G pullout. The objective is to keep the airplane at the desired gravity level for the longest time within the capability of the airplane. The parameter of most concern is acceleration along the vertical or Z axis of the airplane.

Tables I through VIII contain data taken from 389 maneuvers executed at various gravity levels from 0G to 0.75G. The data was collected during project flying. The maneuvers were flown within a 7-day period off the coast of Pensacola, Florida. Generally, fair weather prevailed with very little turbulence during the entire period. All maneuvers were executed by two pilots who alternately changed from pilot to co-pilot duties. During each flight, several maneuvers (usually 6) were flown at each gravity level, making it necessary to adjust the instrumentation system for each gravity level on every flight. Four data points were taken during each maneuver at 2-second intervals, the first data point being 2 seconds after reaching the desired gravity level. The extreme errors are shown for each flight at each G-level, along with the average error for all data points on that flight. Generally, a zero-gravity maneuver is considered acceptable if kept within ± 0.05G. This includes both instrumentation and pilot errors. Table I reveals only one data point out of tolerance for 44 zero-G maneuvers. The extreme errors for 0.05G, 0.1G, and 0.17G (lunar gravity) are all within the acceptable range. Consequently, all the averages are within the desired tolerance. However, at 0.2G and above, there are an increasing number of errors out of tolerance. It also is apparent that the average errors are more negative at the lower gravity levels and more positive at the higher gravity levels.

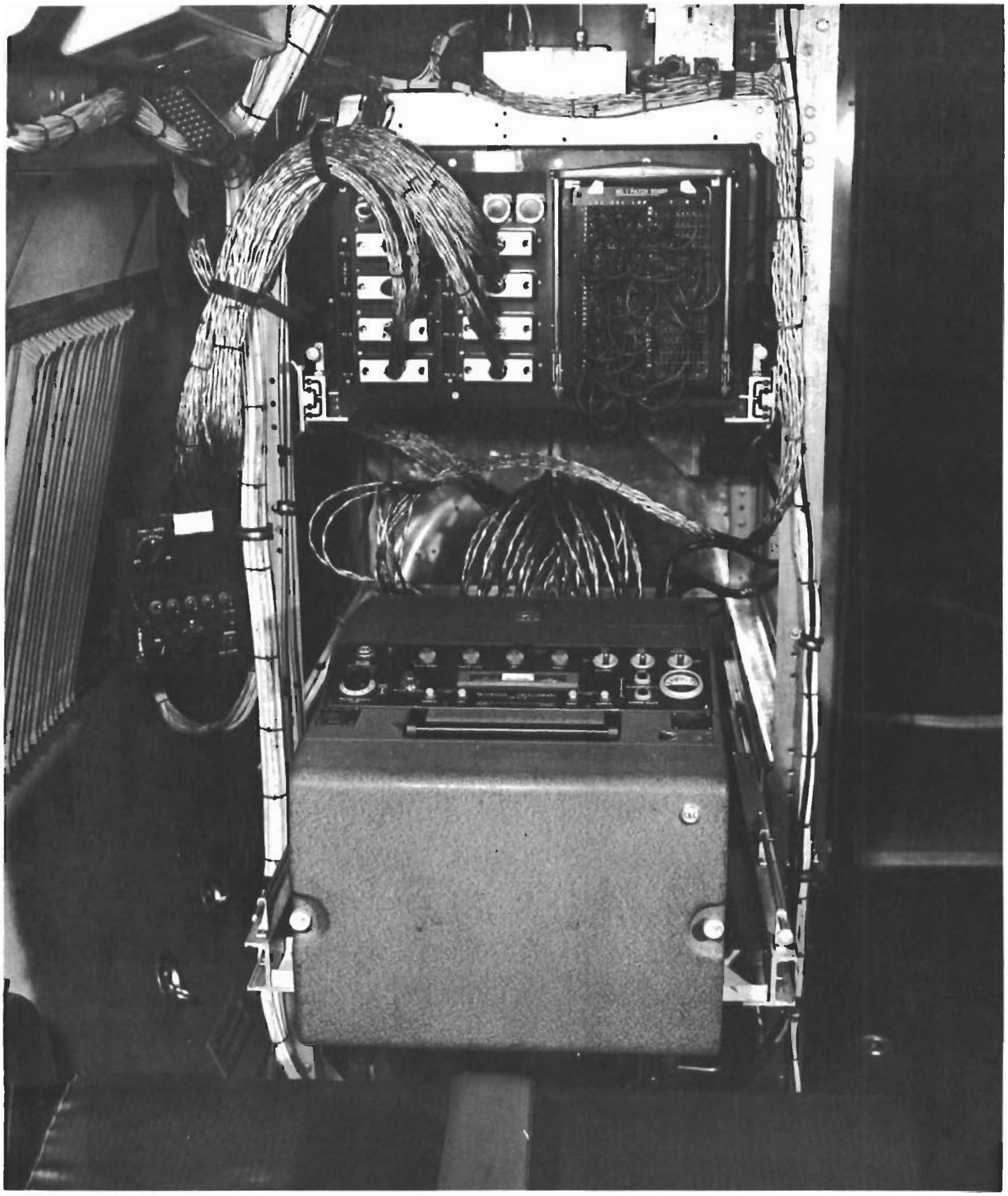


Figure 24

RECORDER MOUNTED IN AIRCRAFT

TABLE I

ZERO-G DATA

FLIGHT NO.	EXTREME ERROR	AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	-0.02 +0.02	-0.012	6	24
2	-0.045 +0.02	-0.028	6	24
3	-0.045 +0.015	-0.016	7	28
4	-0.045 +0.055	+0.025	6	24
5	-0.04 -0.02	-0.027	6	24
6	-0.035 +0.025	-0.023	13	52

TABLE II

0.05-G DATA

FLIGHT NO.	EXTREME ERROR		AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	-0.045	+0.025	-0.014	6	24
2	-0.025	+0.03	-0.012	6	24
3	-0.04	+0.04	+0.02	7	28
4	-0.04	+0.02	-0.022	5	20
5	-0.02	+0.03	+0.015	6	24
6	-0.04	+0.025	+0.014	6	24
7	-0.04	+0.035	-0.015	6	24
8	-0.035	+0.025	-0.013	6	24

TABLE III

0.1-G DATA

FLIGHT NO.	EXTREME ERROR		AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	-0.025	+0.02	-0.011	6	24
2	-0.045	+0.025	-0.018	6	24
3	-0.06	+0.05	-0.017	6	24
4	-0.05	0	-0.019	5	20
5	0	+0.05	+0.021	6	24
6	-0.02	+0.025	+0.012	6	24
7	-0.015	+0.025	+0.009	6	24
8	-0.03	+0.02	-0.011	6	24

TABLE IV

0.17-G DATA

FLIGHT NO.	EXTREME ERROR		AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	-0.035	+0.005	-0.023	6	24
2	-0.05	0	-0.027	6	24
3	-0.025	+0.03	+0.014	6	24
4	-0.045	-0.01	-0.027	6	24
5	-0.025	+0.015	-0.01	6	24
6	-0.04	+0.005	-0.017	5	20
7	-0.02	+0.025	+0.01	6	24
8	0	+0.04	+0.02	3	12
9	-0.035	+0.025	+0.012	4	16

TABLE V

0.2-G DATA

FLIGHT NO.	EXTREME ERROR		AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	0	+0.045	+0.02	6	24
2	-0.035	+0.02	-0.011	6	24
3	-0.005	+0.03	+0.13	2	8
4	0	+0.05	+0.022	5	20
5	+0.01	+0.06	+0.027	6	24
6	-0.015	+0.02	+0.009	6	24
7	0	+0.06	+0.037	6	24
8	+0.02	+0.055	+0.036	6	24
9	-0.02	+0.06	+0.028	6	24

TABLE VI

0.33-G DATA

FLIGHT NO.	EXTREME ERROR		AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	+0.01	+0.035	+0.023	6	24
2	-0.03	+0.04	-0.012	6	24
3	-0.02	+0.01	-0.007	6	24
4	-0.005	+0.04	+0.018	6	24
5	-0.01	+0.03	+0.01	6	24
6	+0.025	+0.07	+0.042	6	24
7	-0.005	+0.065	+0.013	6	24
8	+0.01	+0.06	+0.034	6	24
9	+0.015	+0.065	+0.033	4	16

TABLE VII

0.5-G DATA

FLIGHT NO.	EXTREME ERROR		AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	-0.005	+0.06	+0.019	8	32
2	-0.01	+0.05	+0.024	7	28
3	+0.015	+0.08	+0.042	7	28
4	-0.015	+0.06	+0.016	6	24
5	+0.035	+0.09	+0.06	6	24
6	+0.025	+0.08	+0.052	6	24
7	+0.015	+0.095	+0.058	6	24
8	-0.02	+0.02	+0.011	2	8
9	-0.02	+0.055	+0.024	5	20

TABLE VIII

0.75-G DATA

FLIGHT NO.	EXTREME ERROR		AVERAGE ERROR	NO. PARABOLAS	NO. DATA POINTS
1	+0.04	+0.09	+0.06	4	16
2	+0.065	+0.13	+0.089	6	24
3	-0.035	+0.015	-0.003	6	24
4	+0.03	+0.10	+0.057	6	24
5	+0.0	+0.065	+0.027	6	24
6	+0.05	+0.11	+0.089	4	16
7	-0.045	+0.005	-0.027	6	24
8	+0.005	+0.065	+0.040	6	24

The error change from 0 to 0.75G is not linear, but progresses toward more positive errors as the G level is increased. Figure 25 through 30 are photographs of typical data collected during a parabola improvement test flight. The horizontal director needle of the ADI was instrumented in order to separate system errors from pilot errors. The ± 0.05G error lines represent ± 0.58 Centimeter (0.23 inch) needle deflection from center. The differential between the needle trace and the accelerometer trace represents system error. The 0-G parabola, Figure 25, reveals an error of +0.03G within the system. The maximum needle error was -0.03G at the nine second time line. The parabola was within tolerance for 13 seconds. Under ideal conditions, the maximum zero-G time for the C-131B aircraft is 15 seconds.

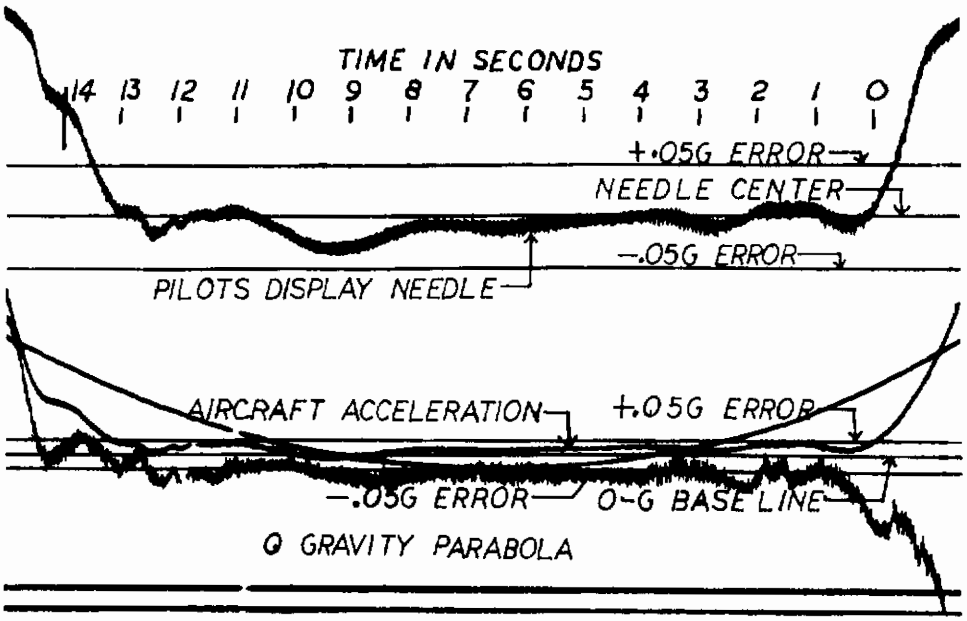


Figure 25

0 GRAVITY PARABOLA

The 0.1G parabola, Figure 26, reveals a +0.025 error in the system. The maximum needle error again is -0.03G at the nine second time line. The needle was within tolerance for 14 seconds indicating the pilot flew the airplane on an accurate maneuver for 14 seconds, but due to system error the actual within tolerance time was 12 seconds. The 0.2G parabola, Figure 27, again has a +0.25G system error. The within tolerance time is 15 seconds. A change in needle error begins to show at this gravity level. The maximum needle error is -0.05G resulting from an overshoot while entering the maneuver. It can be noted at this point that a near asymptotic approach was made at 0-G, a small overshoot of -0.025G was experienced upon entering 0.1G and at 0.2G the overshoot became a -0.05G error at the four second time line.

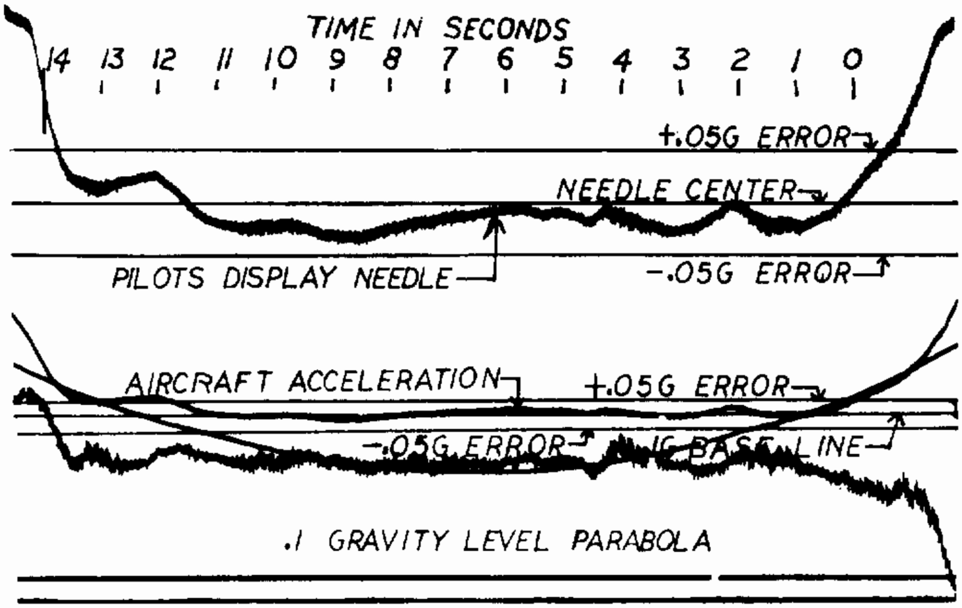


Figure 26

0.1 GRAVITY LEVEL PARABOLA

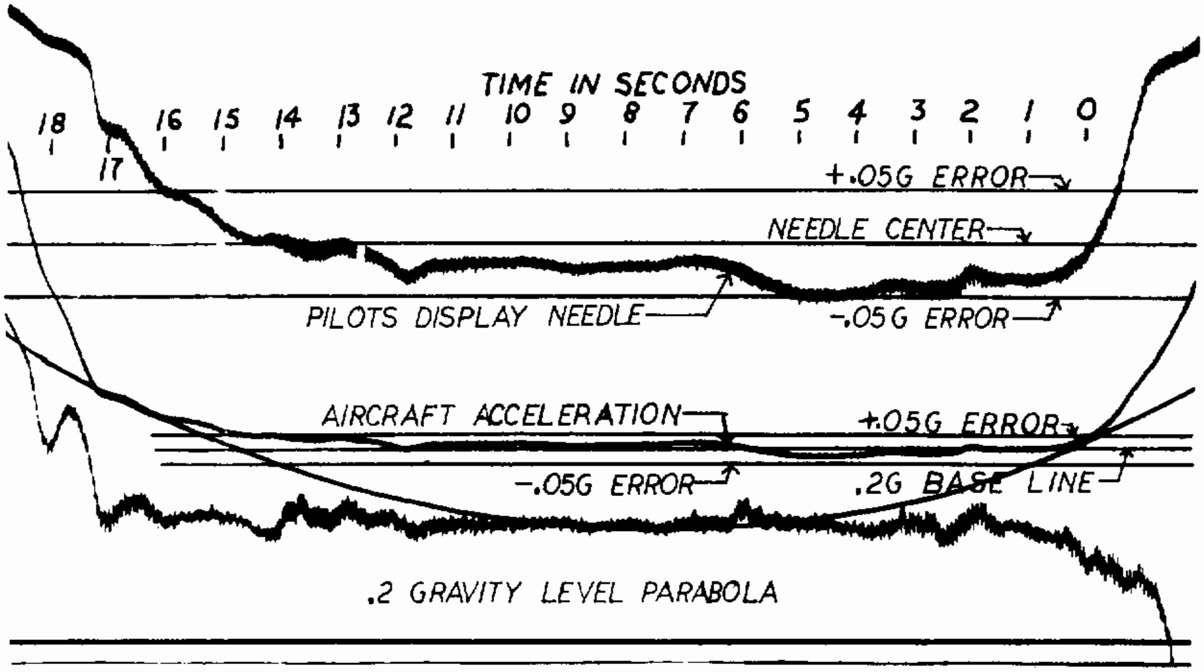


Figure 27

0.2 GRAVITY LEVEL PARABOLA

In flying the 0.2G parabola, the pilot was within tolerance for 16.5 seconds, but due to the error in the display system, the aircraft was within tolerance for only 14.5 seconds. As the desired gravity level is increased to 0.3G, Figure 28, the system error has increased to +0.04G. This error has limited the aircraft actual within tolerance time to 6 seconds out of 15 seconds of within tolerance flying (per instruments). Again, the initial overshoot at entry is present with a gradual increase from a negative to a positive needle. The 0.4G and 0.5G parabolas, Figures 29 and 30, the system error has increased to 0.05G, the overshoot error has increased and the within tolerance error has reduced to approximately 5 seconds. At 0.5G, the aircraft is capable of a 25 second maneuver, but due to excessive system errors and human errors in making in-flight adjustments to the system, the within tolerance time was reduced to 5 seconds. The additional 20 seconds is useful, but makes project data reduction more complex. It can be noted from this data that as the gravity level increases, the system error increases and the parabola becomes increasingly more difficult to fly within tolerable accuracies.

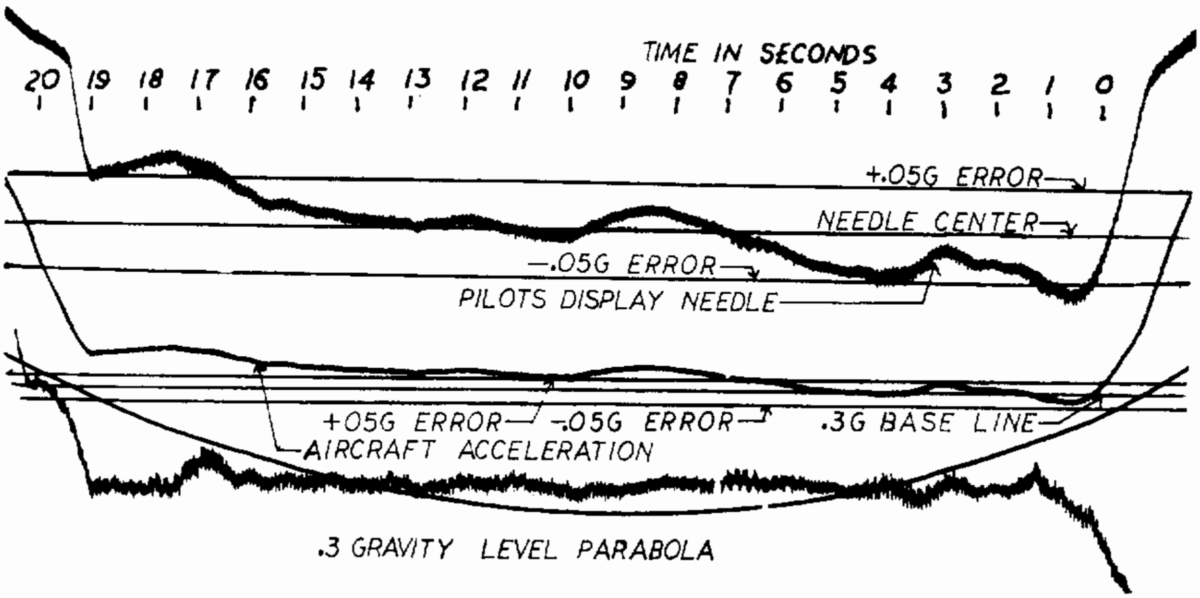
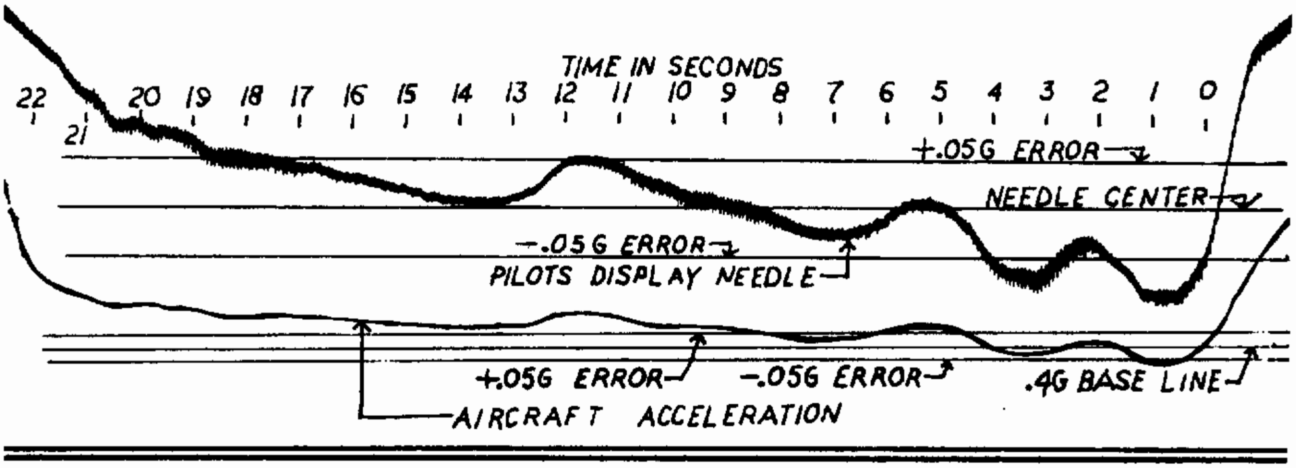


Figure 28

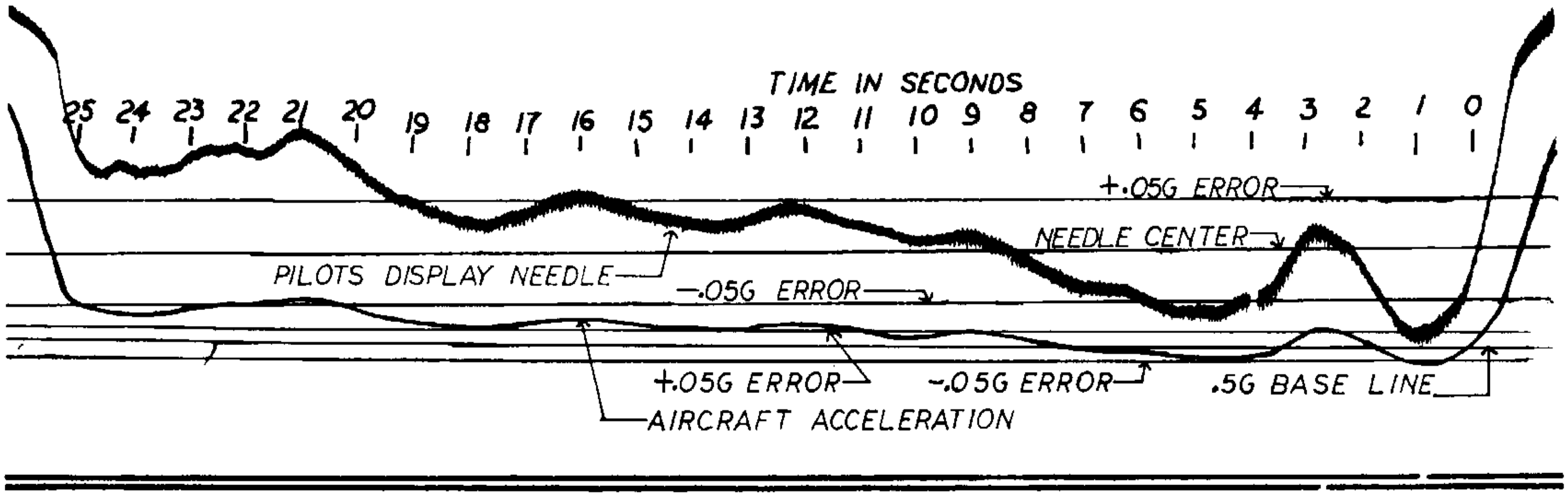
0.3 GRAVITY LEVEL PARABOLA



.4 GRAVITY LEVEL PARABOLA

Figure 29

0.4 GRAVITY LEVEL PARABOLA



.5 GRAVITY LEVEL PARABOLA

Figure 30

0.5 GRAVITY LEVEL PARABOLA

On several project flights, a series of decay maneuvers was flown at the end of the flight to evaluate the maneuver. Decay maneuvers have only been used for one program. Thus far, they are the most difficult to fly. However, after approximately 8 or 10 maneuvers, a zero-G pilot can execute a relatively smooth decay maneuver.

When flying zero-G maneuvers, the longitudinal acceleration is maintained at zero by continuous throttle adjustments using a floating object as a reference. It is impossible to use this method to control fore and aft accelerations when flying subgravity maneuvers. A longitudinal acceleration display system was therefore installed. It consists of a Donner Model 4310 ± 1 G accelerometer, rigidly mounted to the airframe center of gravity, driving a standard 6.35 Centimeter (2.5 inch) microammeter mounted under the co-pilot glare shield. The indicator has a ± 50 micro-amp movement and a scale designed to read ± 0.2 G for full displacement. As a result of this installation, the fore and aft accelerations have been greatly reduced during subgravity maneuvers.

IV CONCLUSIONS

The Parabola Control Panel was designed as experimental equipment to evaluate various methods of presenting zero and reduced gravity information on an Attitude Director Indicator (ADI). It has proven to be an effective instrument on which to present such information to the pilot. Most of the technical problems encountered with the system were due to inferior components which had been removed from various pieces of used surplus equipment. The study has shown a need for a similar but electrically more stable system and has demonstrated which modes are desirable and which modes may be eliminated from a subsequent system. Basic design of the system was very good considering the components used; however, there are areas where design changes should be made in a new system.

Data collected during this study suggests that the full capability of the aircraft cannot be utilized as long as the maneuvers are flown manually. Due to this, a new system should provide for an eventual automatic control tie-in which could add several seconds to each maneuver and provide more consistent and more accurate maneuvers.

V RECOMMENDATIONS

A new parabola control panel should be designed exclusively for a display system emphasizing higher quality which will require more stable components and less complex checkout and operating procedures. If possible, transistorized components should be used to conserve space and weight. The design should limit all in-flight adjustments to turning a switch or pushing a button at most. All critical adjustments and alignments of the equipment should be made on the bench or during aircraft down time.

A desirable feature would be to make provisions to tie in a programmer at a later date for fully automatic control.

A semi-automatic control phase of the Parabola Improvement Program should be initiated as soon as practical. This would require a flight controller to be modified to provide ± 50 degrees of pitch control and a modification of the autopilot pitch servo to provide 2.5G instead of the present 2G aircraft loading. During this phase, the pilot will operate the flight controller manually; however, the muscular strain involved will be absorbed by the autopilot which should result in less pilot fatigue and more consistently accurate maneuvers.

The ultimate goal in zero-G flying is a fully automatic controlled maneuver striving for accuracies of ± 0.005G. This could be accomplished with a programmer such as the one described in part 1 of this report. It would, of course, be necessary to have a more stable system to supply information to the autopilot.

BIBLIOGRAPHY

Air Force Technical Orders 5F5-5-3-2, -3, -4, -12, -13, -14, Aircraft Flight Director Computer, Type CPU-4/A.

Air Force Technical Orders 5F6-3-5-3, -4, -13, -14, Gyroscope, Roll and Pitch Displacement, Type MD-1.

Air Force Technical Orders 5F6-4-3-3, -4, -13, -14, Gyroscope, Switching Rate, Type MC-1.

Air Force Technical Orders 5F8-3-11-2, -3, -4, Indicator, Attitude Director, Type ARU-2/A.

Air Force Technical Order 5A1-2-8-1, Automatic Pilot USAF Type E-4.

Air Force Technical Order 1C-131B-2-9, Wiring Data USAF Series C-131B Aircraft.

Hammer, Lois R., Aeronautical Systems Division Studies in Weightlessness: 1959-1960, WADD Technical Report 60-715 (AD 273 098), Wright Air Development Division, Wright-Patterson Air Force Base, Ohio, December 1961.

KC-135 Modification for Zero-Gravity Flight, Boeing Airplane Company, Aero Space Division, Technical Proposal D2-5358, Seattle, Washington.

Mueller, Donald D., The Coriolis Effect in Zero-Gravity Research Aircraft, AMRL Memorandum P-9 (AD 284 049), 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, June 1962.

Sears, C. W., and Bunch, E. P., Modification to ASD Weightless Aircraft, C-131B Serial Number 53-7806, AMRL Memorandum P-41 (AD 417 439), 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, July 1963.

Weiss, R., Display Systems for Sub- and Zero-Gravity Flights, AMRL Technical Documentary Report 63-11 (AD 402 382), 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, January 1963.

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Lear Siegler Service, Inc. 6700 Allentown Blvd. Harrisburg, Pa. 17112	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

ZERO-GRAVITY MANEUVER INSTRUMENTS AND INSTRUMENTATION

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report April 1964 - April 1965

5. AUTHOR(S) (Last name, first name, initial)

Dixon, B. C.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1966	50	none

8a. CONTRACT OR GRANT NO. AF 33(657)-11107 b. PROJECT NO. 7184 c. Task No. 718405 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AMRL-TR-66-1

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Aerospace Medical Research Laboratories Aerospace Medical Division, Air Force Systems Command, Wright-Patterson AFB, Ohio

13. ABSTRACT

The type ARU-2B/A Attitude Director Indicator (ADI) system was evaluated as a pilot aid in flying a JC-131B aircraft on a ballistic trajectory to produce a zero- or reduced-gravity field. To provide an unburdened display to the pilot, all information necessary to fly a complete zero-G maneuver was presented on the ADI, except airspeed. A Parabola Control Panel was designed to provide six modes of presenting normal acceleration data to the ADI; i.e., zero-G, sub-G, super-G, decay, float, and program modes. The modes were effective, except for the float and program modes which are still experimental. Data from 385 maneuvers at various gravity levels from 0 G to 0.75 G revealed that when flying gravity levels below 0.25 G an accuracy of ± 0.05 G could be maintained. This is generally considered an acceptable parabola. However, when flying gravity levels greater than 0.25G the errors became greater than + 0.05G. As the desired gravity level is increased, the parabola time is increased and a high degree of accuracy is more difficult to maintain. In addition, the system errors were greater at the higher gravity levels. These two facts account for most of the errors at increased sub-gravity levels. The ARU-2B ADI system proved to be an effective aid in flying various sub-G, super-G, zero-G, and decay maneuvers.

DD FORM 1 JAN 64 1473

Security Classification

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Programmer Accelerometer Amplifiers Indicator Instrumentation Maneuver						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
____."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
____."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
____."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Security Classification