# INVESTIGATION OF "PREDICTOR" DISPLAYS FOR ORBITAL RENDEZVOUS

## PROGRAM SUMMARY

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# FOREWORD

This study was a joint effort undertaken by Ritchie, Inc., Dayton, Ohio, working under contract AF 33(615)-1089 and the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories and sponsored by National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, under NASA DPRW-11615-B. The Aerospace Medical Research Laboratories portion of the work was in partial support of Project 7184, "Human Performance in Advanced Systems," Task 718402, "Criteria for the Design of Controls and Control Systems." William K. McCoy, Jr. was the Principal Investigator for Ritchie, Inc., and George G. Frost, Maintenance Design Branch, Human Engineering Division of the Behavioral Sciences Laboratory, was the Technical Monitor for the Air Force.

The first year's work was supported by NASA Manned Space Center, Houston, Texas (NASA DPRW-11615-B). The display format was conceived and developed by A. G. Berbert, Jr. of Ritchie, Inc. and G. G. Frost of AMRL.

The first phase of this program was begun in November 1963 and was completed in October 1964.

This technical report has been reviewed and is approved.

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# ABSTRACT

A series of studies on the development of predictor display techniques for orbital rendezvous is summarized. The purpose of this program was to evaluate alternative predictive display techniques for orbital rendezvous. After an analog simulation of the rendezvous problem was mechanized and a display format developed, two studies were conducted investigating operator efficiency at control of rendezvous utilizing the side looking display format and predictor display techniques. Also, two display modifications were investigated: a reduced display size and, the addition of a braking circle.

The results of the initial work indicated that operator performance in manual control of rendezvous maneuvers was enhanced by predictor display techniques. The final section of the report outlines the plans for follow-on efforts.

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# PROGRAM SUMMARY

## Introduction and Overview

The purpose of this program was to evaluate alternative predictive display techniques[1] and to investigate prediction span, initial separation, initial relative velocity between vehicles, and display complexity. The predictor display techniques investigated utilized fast-time computation of the system equations of motion to provide predicted future states of the system. These predictive display techniques are intended for application to orbital rendezvous and lunar landing. Due to time limitations only rendezvous problems were studied. Preliminary efforts were directed toward a literature review of past work in developing the predictor instrument and in delineating important factors for orbital rendezvous and lunar landing.

A display format was developed and a rendezvous task determined. Several studies were accomplished to evaluate the predictor display as an aid to a human operator performing an orbital rendezvous. Results of these studies indicated that the predictor display significantly improved operator performance of rendezvous. The final efforts on this project were directed toward a major modification of the rendezvous task to conform to the currently planned Gemini mission.

## Development of the Analog Simulation

An analog computer was programmed to simulate the orbital mechanics of a general rendezvous problem. The interceptor vehicle was attitude stabilized so that the vehicle X- and Y-axes were always parallel with the coordinate system axes. The target vehicle and interceptor are shown in figure 1, and the coordinate system shown in figure 2. The equations of motion that follow were reported by Mueller in 1962 (ref 2).

$$\ddot{X} = f_X - 2\omega\dot{Y}$$

$$\ddot{Y} = f_Y + 2\omega\dot{X} + 3\omega^2 Y$$

$$\ddot{Z} = f_Z - \omega^2 Z \quad \text{(if coplanar orbits are assumed } Z = 0\text{)}$$

where $\ddot{X}$, $\ddot{Y}$ and $\ddot{Z}$ = X, Y, and Z accelerations of the interceptor

$f_X$, $f_Y$, and $f_Z$ = X, Y, and Z, components of external force per unit mass on the interceptor (exclusive of gravity)

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[1] The concept of predictor displays was first explored by Dr. Charles R. Kelley of Dunlap & Associates.

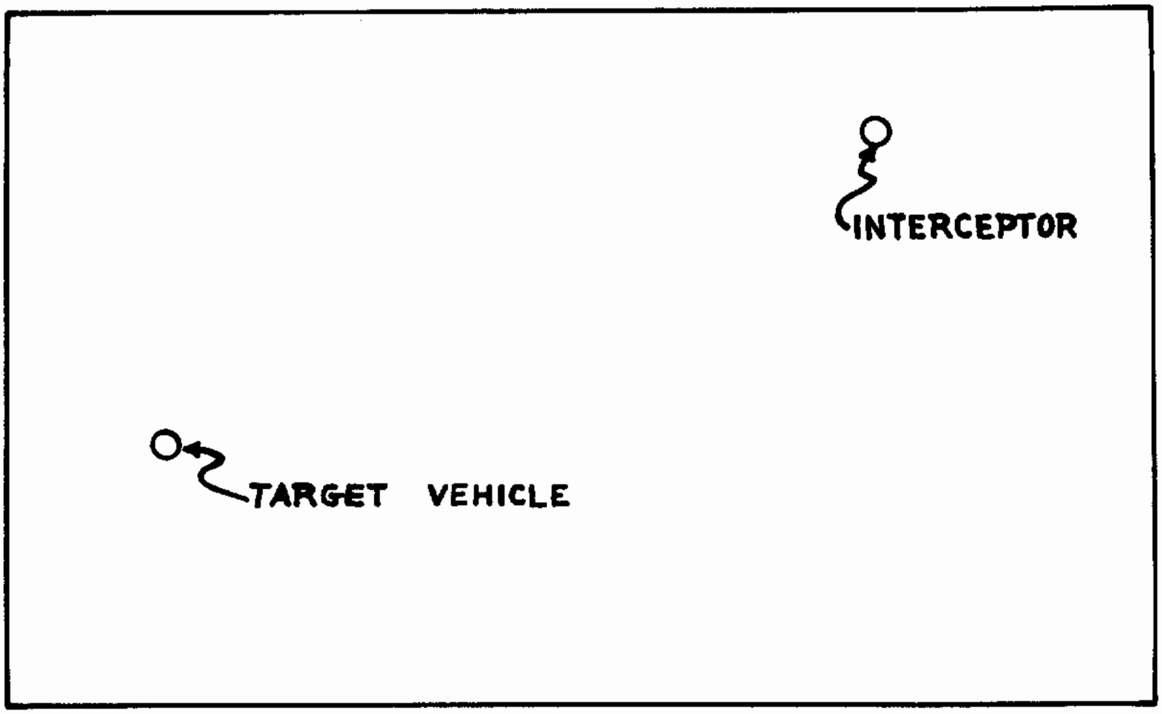

Figure 1. Profile of the X-Y plane.

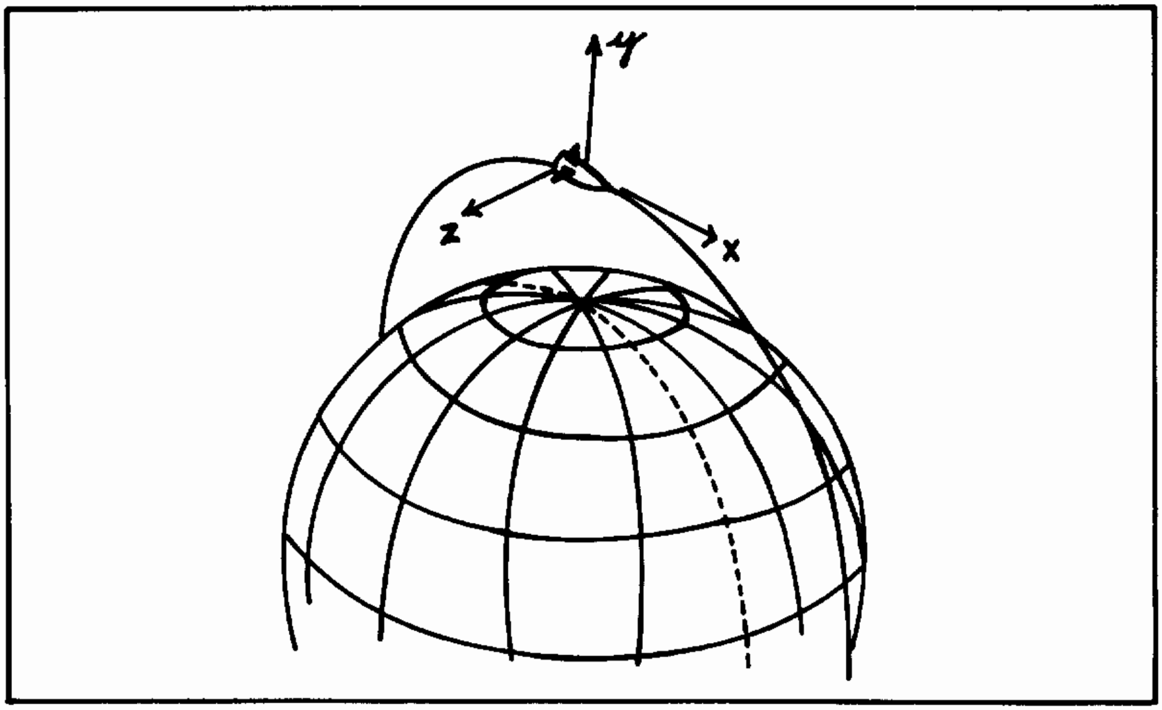

Figure 2. Coordinate system.

$\dot{X}$ and $\dot{Y}$ = X and Y velocities of the interceptor

$\omega$ = angular velocity of the rotation of the coordinate system relative to inertial space (for a 200 nautical mile orbit

$\omega$ = .00114 radians/second)

In this project coplanar orbits were assumed.

After considerable analytical effort a display format was developed and a profile display mode conceived. The profile is of the X-Y plane and the display shows the target and the interceptor in their relative positions (figure 1). For the initial pilot work an X-Y plotter was used for a display. Later when the predictor was mechanized, cathode-ray tube (CRT) displays were utilized.

After trying a two-axis on-off switch as a controller a two-axis stick allowing simultaneous and proportional control of X and Y acceleration was instrumented. Near the target, subjects wanted to be able to put in small corrections simultaneously in x and y velocity.

## Rendezvous Task

A rendezvous task was developed. The interceptor started from various starting positions, all above and ahead of the target vehicle. Several initial starting rates were examined. The operator's task was to perform a rendezvous within a fixed time using as little fuel as possible.

## Operator Performance Variables

Once a profile display mode was selected three display configurations were conceived: (1) only the target and the interceptor displayed (figure 1), (2) a time history of the interceptor's path displayed (figure 3), and (3) a predicted path of the interceptor displayed (figure 4).

We hypothesized that operator performance in making a rendezvous would improve as the information about his orbital path increased. Analyses indicated that, of the three display configurations described above, most information would be provided by the predictor that displayed what the interceptor would do as a result of a given control input. Less information would be provided by a display of a time history that provides visual cues concerning the past response of the system resulting from prior control inputs thus permitting the operator to extrapolate what the system will do in the immediate future. The least information would be provided by a display with neither a time history nor a prediction, but simply present relative position.

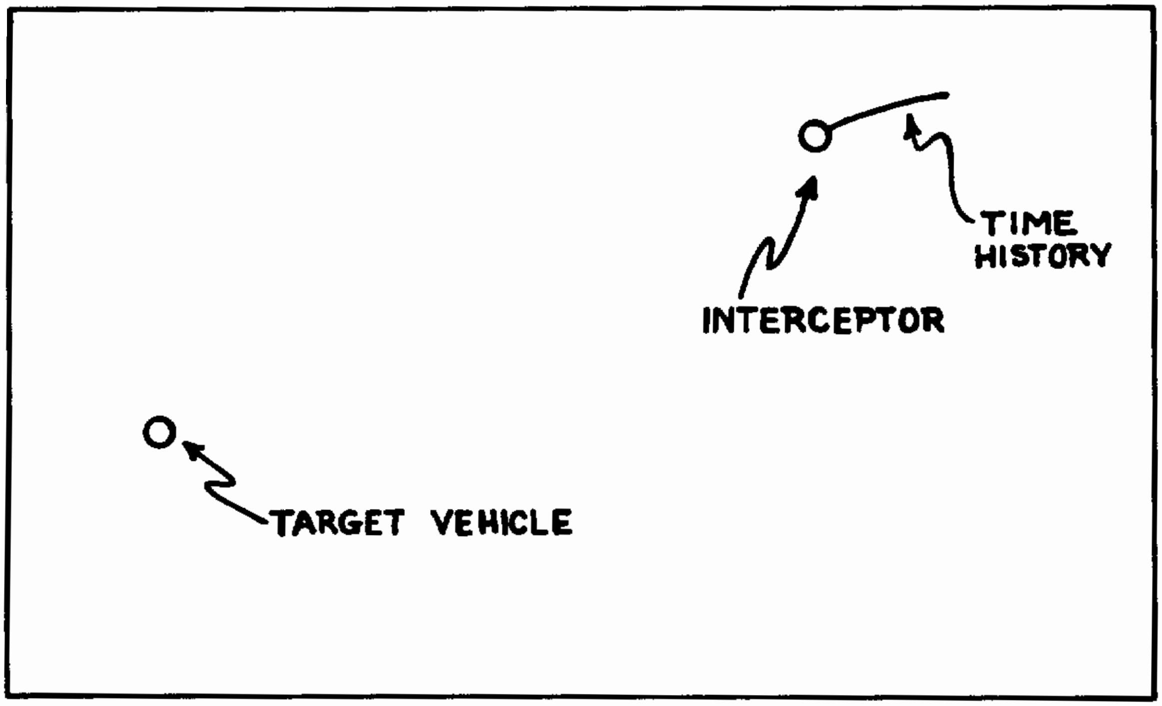

Figure 3. Profile of the X-Y plane with time history.

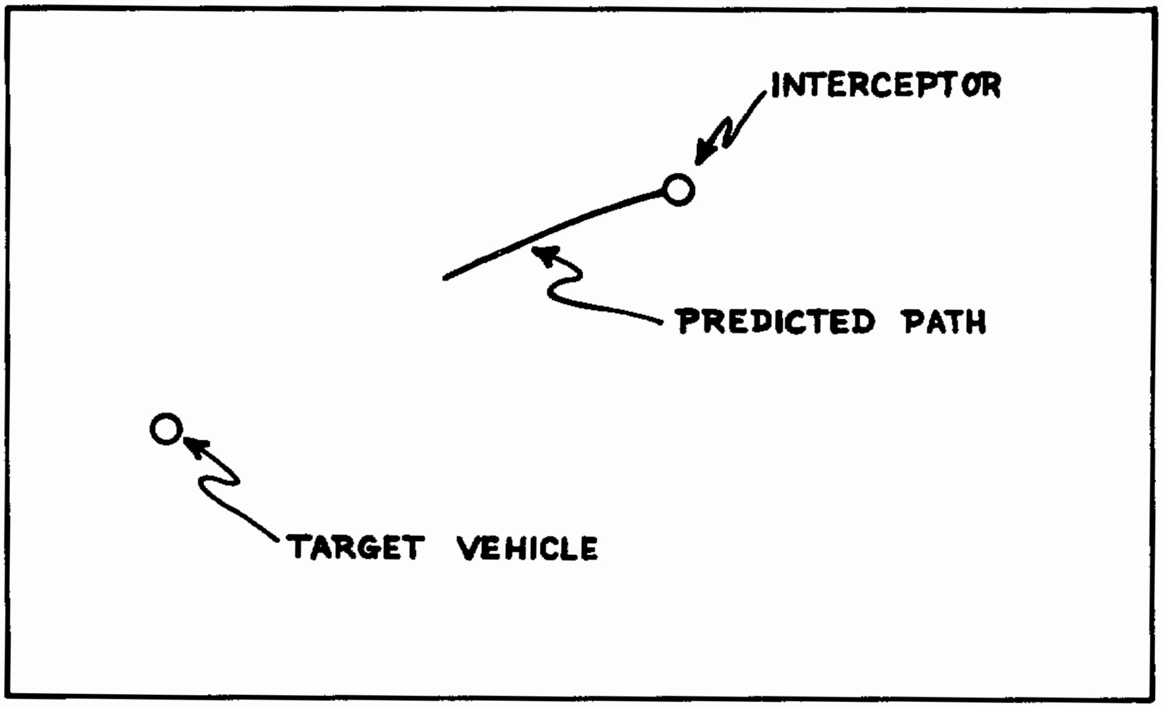

Figure 4. Profile of the X-Y plane with predicted path.

## Time History vs. No Time History

The first study compared time history and no time history as information sources for operator control of orbital rendezvous (ref 1).

Criteria for evaluating operator performance of a rendezvous were: (1) total velocity increment (ΔV)* for the rendezvous maneuver, (2) range and range-rate in X and Y at the end of a maneuver, (3) control stick movements in X and Y during a rendezvous maneuver and (4) records of orbital path flown to accomplish rendezvous.

Three sets of X and Y starting rates were used as initial conditions from starting position of 80,000 ft (24,384 meters) ahead and 20,000 ft (6,096 meters) above the target vehicle. These values were as follows:

| | X Rate | Y Rate |
|---|---|---|
| IC 1 | 151.25 ft/sec (46.10 m/sec) | 41.25 ft/sec (12.57 m/sec) |
| IC 2 | 151.25 ft/sec (46.10 m/sec) | 37.50 ft/sec (11.43 m/sec) |
| IC 3 | 123.75 ft/sec (37.72 m/sec) | 30.00 ft/sec (9.14 m/sec) |

Eight subjects were used in a counterbalanced experimental design, and each subject received all conditions. The circuit diagram for the analog simulation used in this study is shown in figure A in Appendix I. For a more detailed description of this study see reference 1.

Results. Operators were able to perform successful rendezvous maneuvers with the profile display under both display conditions (time history and no time history). The criteria for a successful rendezvous were that range and range-rate were to be reduced to 10 ft (3.05 meters) and 1 ft/sec (.3048 m/sec) respectively within 15 minutes. In terms of fuel consumption and control stick movements, significantly better performance was obtained when the time history -- trace -- was present (figure 5). Further, the obtained ΔV (fuel expenditure) scores were less than those that would be obtained from a theoretically perfect line-of-sight orbital transfer but, of course, more than a theoretically perfect two-impulse transfer (figure 6).

## Predictor Display Study

The same criteria for evaluating operator performance of rendezvous in the above study were used in the predictor display study. The circuit diagrams for this

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*ΔV (velocity increment) is proportional to fuel consummed which can be calculated if the vehicle's mass and the specific impulse of the fuel are known.

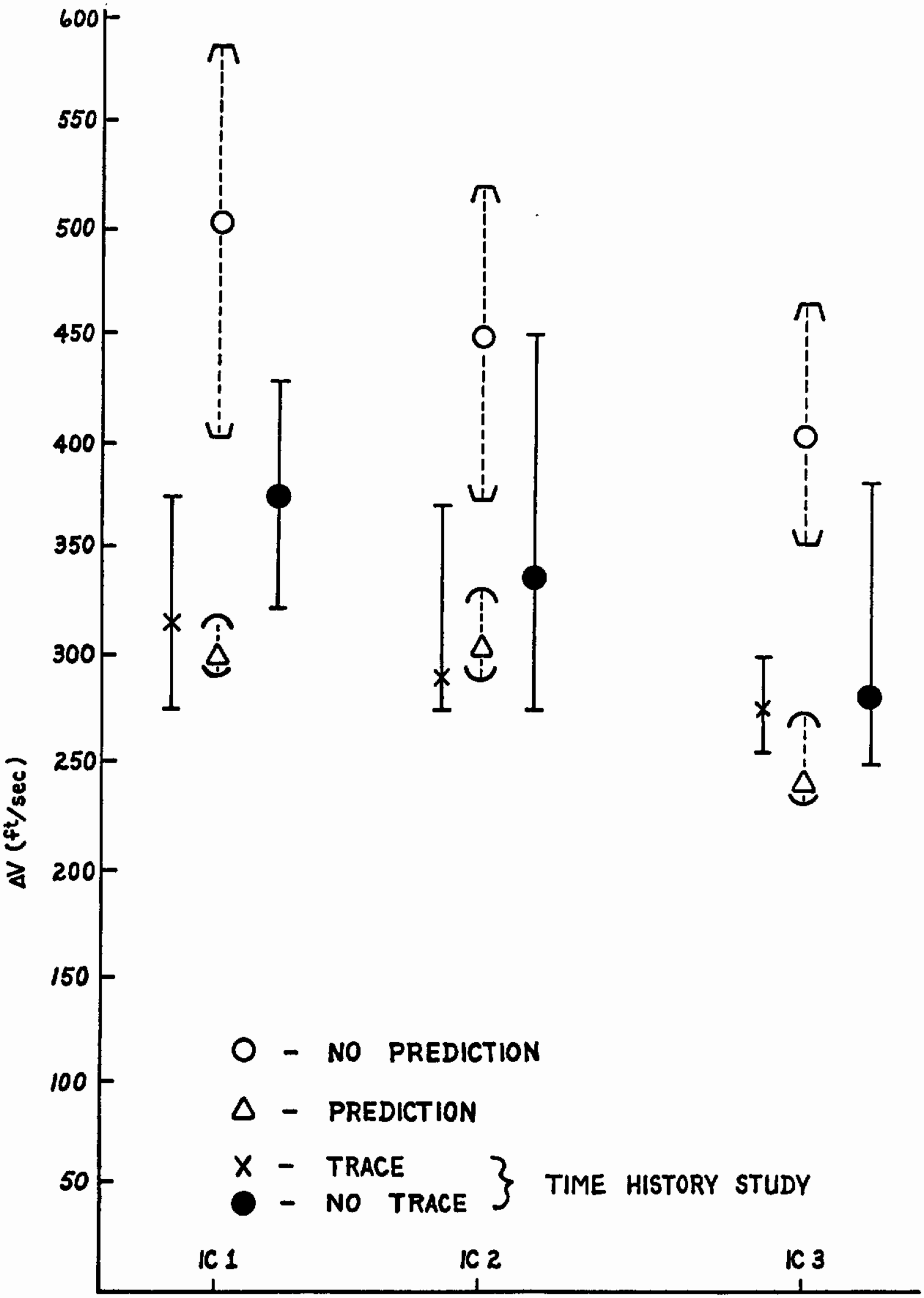

Figure 5. Obtained median ΔV's with the 25th and 75th percentiles indicated.

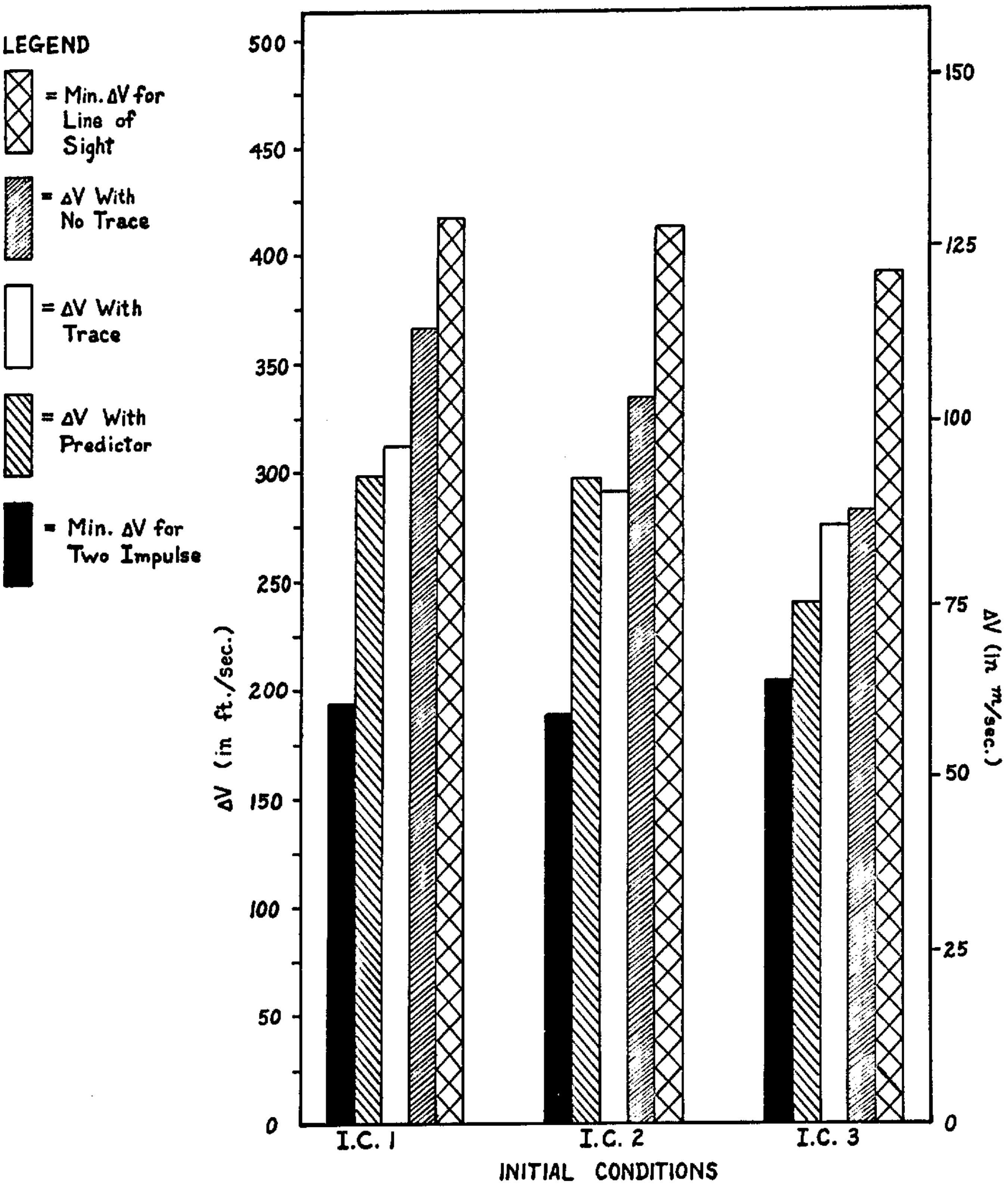

Figure 6. Comparison of obtained median ΔV's with theoretical minimum ΔV's for two impulse and line-of-sight orbital transfers.

simulation are shown in figures B through G in Appendix I. The display was a 17-inch CRT which presented the operator with the present relative position of the interceptor and the target vehicle and a predicted path of the interceptor. Two conditions were compared: prediction and no prediction.

Ten subjects were used in a counterbalanced design with each subject receiving all conditions. Subjects were divided into two groups. One group received 12 trials (4 under each of 3 different initial starting conditions) under the prediction display condition. Then, they received 12 trials under the no prediction display condition. The other group received no prediction trials first; then they received the prediction trials. The order of presentation of initial conditions was also counterbalanced.

Each trial consisted of a rendezvous from an initial starting position of 80,000 feet ahead (24,384m) and 20,000 feet above (6,096m) the target. Three sets of x and y rates were used as initial conditions. These were the same as those used in the time history study and are shown in the table on page 5. The same initial conditions were used to allow comparison of the data obtained in the predictor study to that obtained in the time history study.

These initial conditions required control action by the subjects to avoid an overshoot or an undershoot. It was as though the first impulse of a two-impulse transfer technique had been applied, but not so the best trajectory had been obtained. The subjects had to determine what corrections were necessary to achieve rendezvous and then apply those corrections. Subjects accomplished this by noting the relative position of the predicted path and the target, and estimating the direction that thrust must be applied to put the predicted path on the target. Once a collision course was established, the subjects then had to determine what control inputs would stop the interceptor at the target vehicle and then apply these inputs to complete the rendezvous maneuver.

A successful rendezvous was one in which range and range-rate in each axis were concurrently brought to less than 400 feet (121.92m) and 8 feet/second (2.44 m/second) respectively within 15 minutes from the initiation of the run. Comparator circuits were implemented such that when a subject achieved the criteria for a successful rendezvous, the computer automatically went into "Hold."

Subjects were given a briefing on orbital mechanics as well as specific instructions concerning their task (Appendix II).

<u>Results</u>. As in the first study the profile display mode was satisfactory for presenting relative position information to an operator performing a rendezvous.

The addition of predicted path information significantly reduced fuel consumption ($\Delta V$) (figure 5). Note that the amount of fuel consumed for the no-prediction condition was greater than the amount for the no-trace condition. This may be explained by the absence of a grid on the display in the no-prediction conditions. A 10 by 10-inch grid was used in the trace and no-trace conditions. Subjects found that the grid was very useful in determining both the direction and magnitude of the velocity change necessary for completing a rendezvous. Smoother trajectories were flown from the initial starting position to the target when the predicted path was present (figure 7). Another interesting result was the rapid learning of the task with the predicted path present. Every operator made a successful rendezvous on the first trial and after only three or four trials performance stabilized.

## Display Modification

The predictor display was reduced in size from a 17-inch CRT to a 5-inch CRT. Two highly experienced operators found no difficulty in performing successful rendezvous maneuvers. The display was then further reduced to a 3-inch CRT. The scale factors, when the display was reduced, were 1 inch = 30,000 ft (9,144 meters) initially, then, 1 inch = 3,000 ft. (914 meters), and 1 inch = 300 ft (91 meters) on the scale changes. The criterion for a successful rendezvous was achieving a range and range-rate of 400 ft (121.90m) and 8 ft/sec (2.44 m/sec) respectively within 15 minutes. The experienced operators had some difficulty with the severely reduced scale factor but still were able to perform rendezvous maneuvers successfully.

Addition of Braking Circle. A circle around the target was added to the display. The diameter was proportional to the square of the interceptor's relative velocity and inversely proportional to the maximum acceleration available. This addition allowed the operator to perform "fast" rendezvous since the circle indicated when the operator was required to apply maximum deceleration to avoid overshoot or impact with the target (figure 8). The sequence of "a" through "f" in figure 8 illustrates the operator's strategy for performing a "fast" rendezvous. The operator would accelerate (maximum acceleration) toward the target keeping the predicted path on target (a, b, c). This acceleration continued until the real time position of the interceptor was at the edge of the braking circle. At this point, the operator would reverse the thrust to decelerate (maximum deceleration) still keeping the predicted path on target. Both the predicted path and the braking circle indicate the deceleration (e). The predicted path and braking circle indicate zero relative velocity at intercept (f), thus completing a rendezvous maneuver. Experienced operators used the above procedure to perform a rendezvous maneuver from an initial range of about 15 miles (80,000 ft--24,384 meters ahead, 20,000 ft--6,096 meters above) in less than 5 minutes. Maximum available acceleration was 10 ft/sec$^2$.

## Rendezvous Program Revision

At NASA's request, the predictor program was modified to approximate the Gemini rendezvous trajectory. The intent of this change was to allow investigation

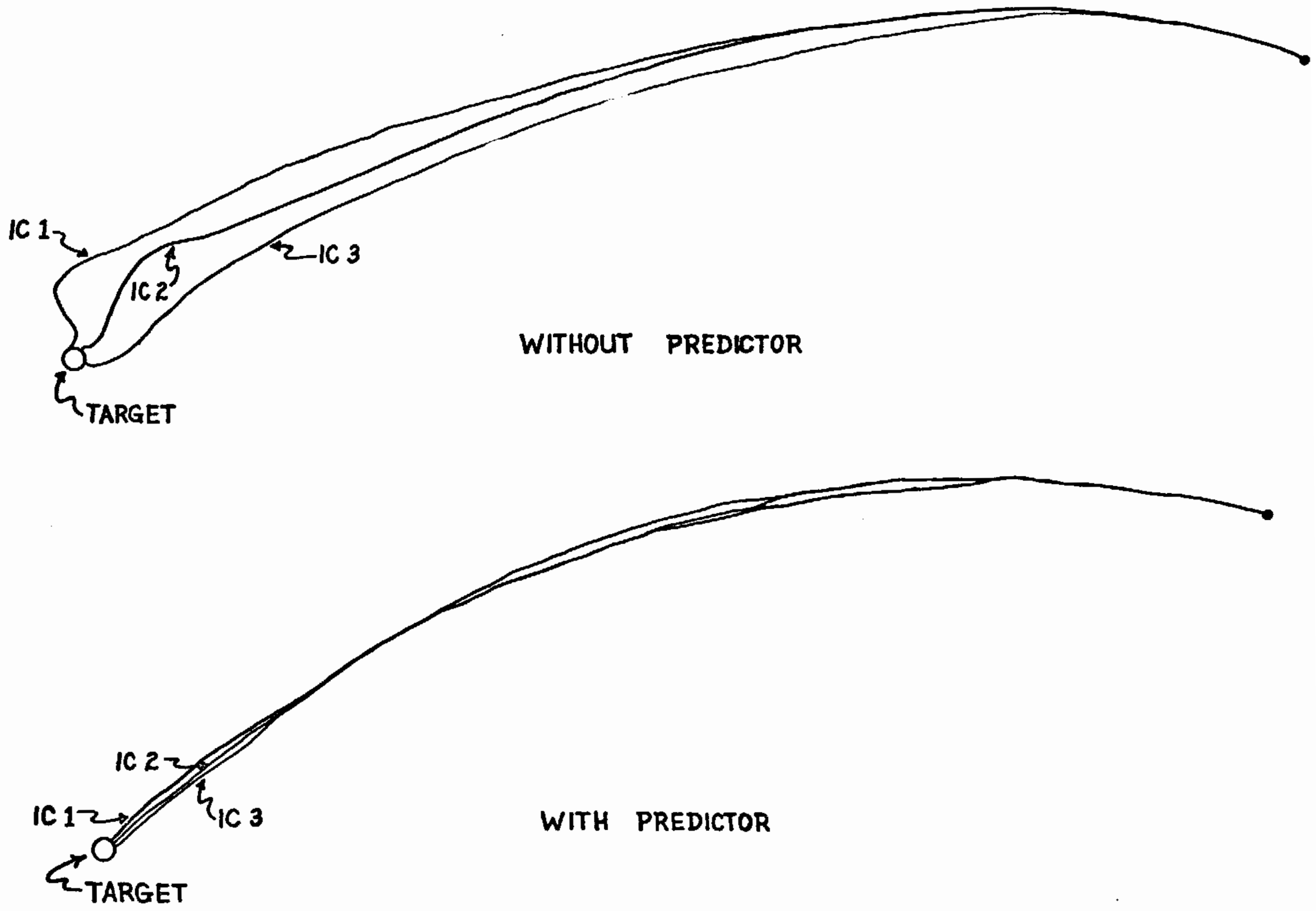

Figure 7. Typical orbital paths to rendezvous.

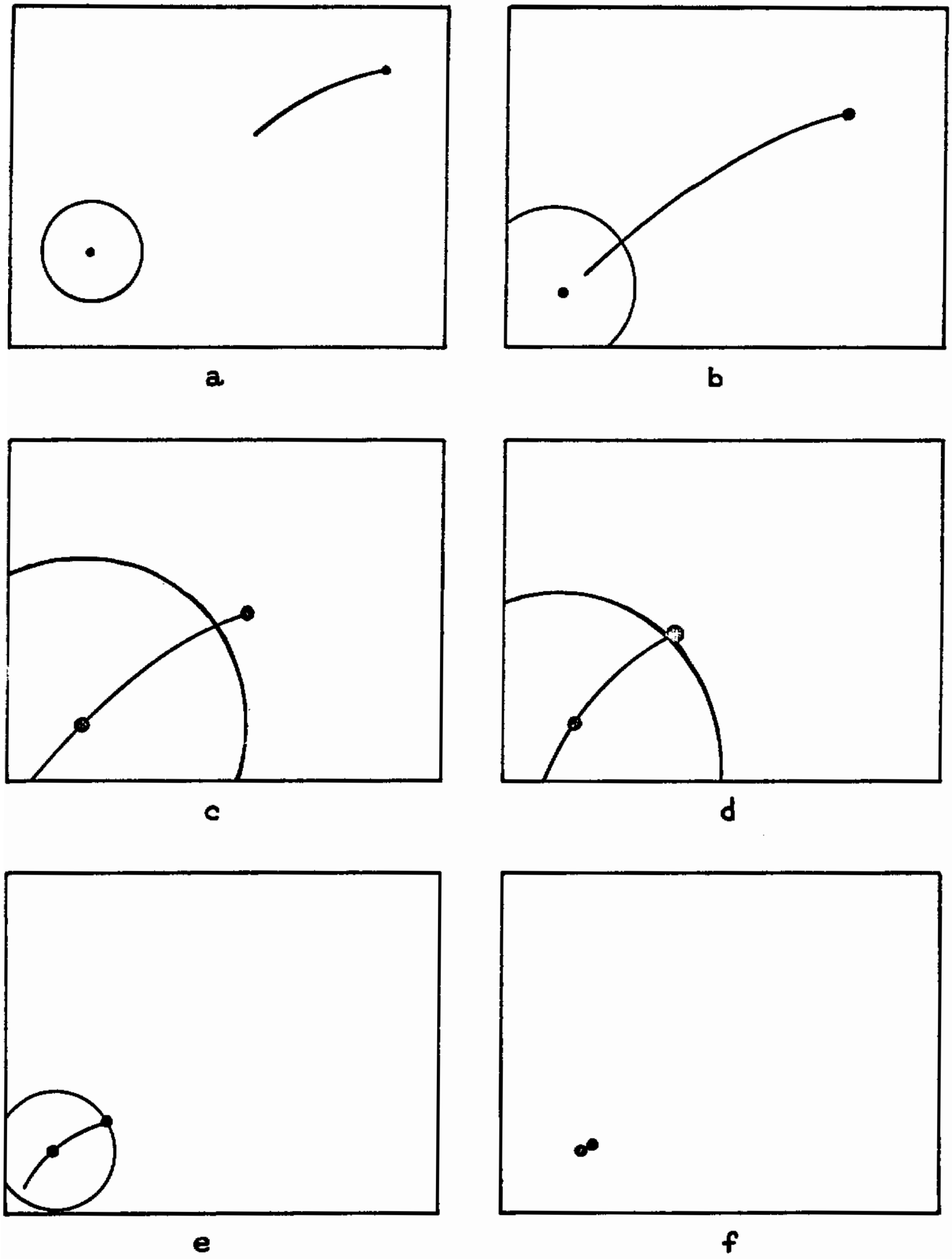

Figure 8. A "fast" rendezvous with a braking circle displayed.

of an off-line predictor for on-board trajectory optimization as a backup guidance mode. Although complete solution of the optimization problem is a sizeable computer problem, we believe that use of an off-line predictor display will allow the pilot to reach a near optimal solution in a short time with a minimum of computer equipment.

The new program assumes a starting position of approximately 275,000 feet (83,875 meters) behind and 120,000 feet (36,600 meters) below the target vehicle. The maneuver will take approximately 37 minutes. The new analog program was determined, but the long (37 minute) integration periods have resulted in an undesirable amount of computational error in obtaining a one to one correspondence with NASA's digital program. The difficulty in obtaining the desired approximation of the digital program has prevented the initiation of studies of these longer ranges.

## Follow-on Work

Future plans in this program include a simulation of the Gemini type rendezvous in half real-time (about an 18 minute rendezvous). This allows handling a long range (about 50 mile) rendezvous problem on existing analog equipment. This time scale which speeds up the entire problem probably will not seriously impair interpretation of the data obtained in future studies. Since the task involves discrete control inputs, and even with the accelerated time scale there will be several minutes between inputs, it seems safe to assume that if operators can successfully perform rendezvous maneuvers with the accelerated time scale, they will successfully perform in real time. The major development to be studied using the Gemini-type rendezvous simulation, is an off-line prediction technique. This refers to a trial prediction system. That is, the fast-time circuits can be utilized to try out maneuvers without applying thrust to the actual vehicle.

Studies will be accomplished to determine: the relative efficiency of on-line and off-line prediction for rendezvous; the effects of radar noise in predictor use; predictor application to non coplanar rendezvous; and the effects of thrust misalignment on the predictor display.

# Appendix I

# Circuit Diagrams for the Analog Simulation of Rendezvous Problems Studied

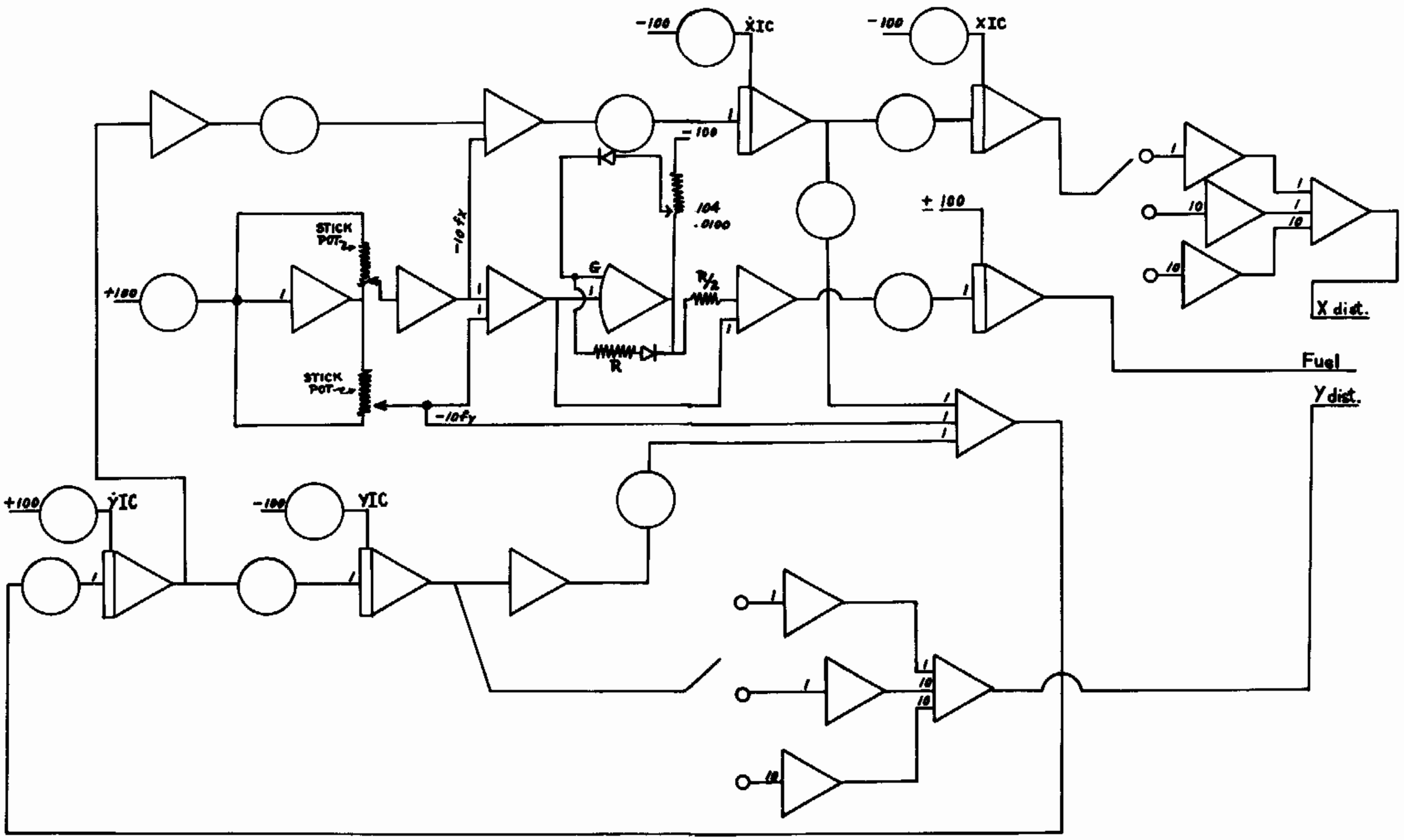

Figure A. Circuit diagram used for analog simulation in the time history study.

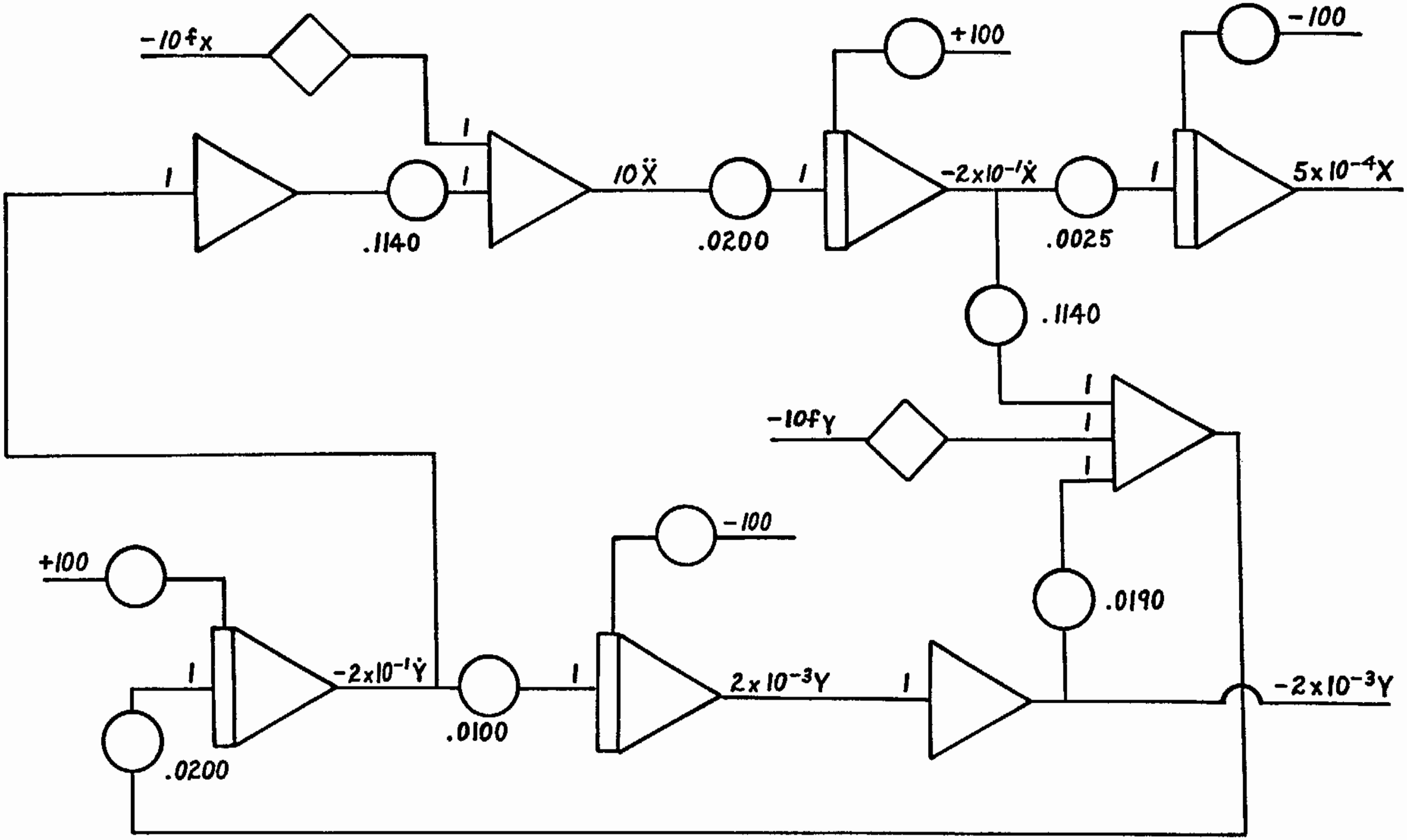

Figure B. Real time circuit.

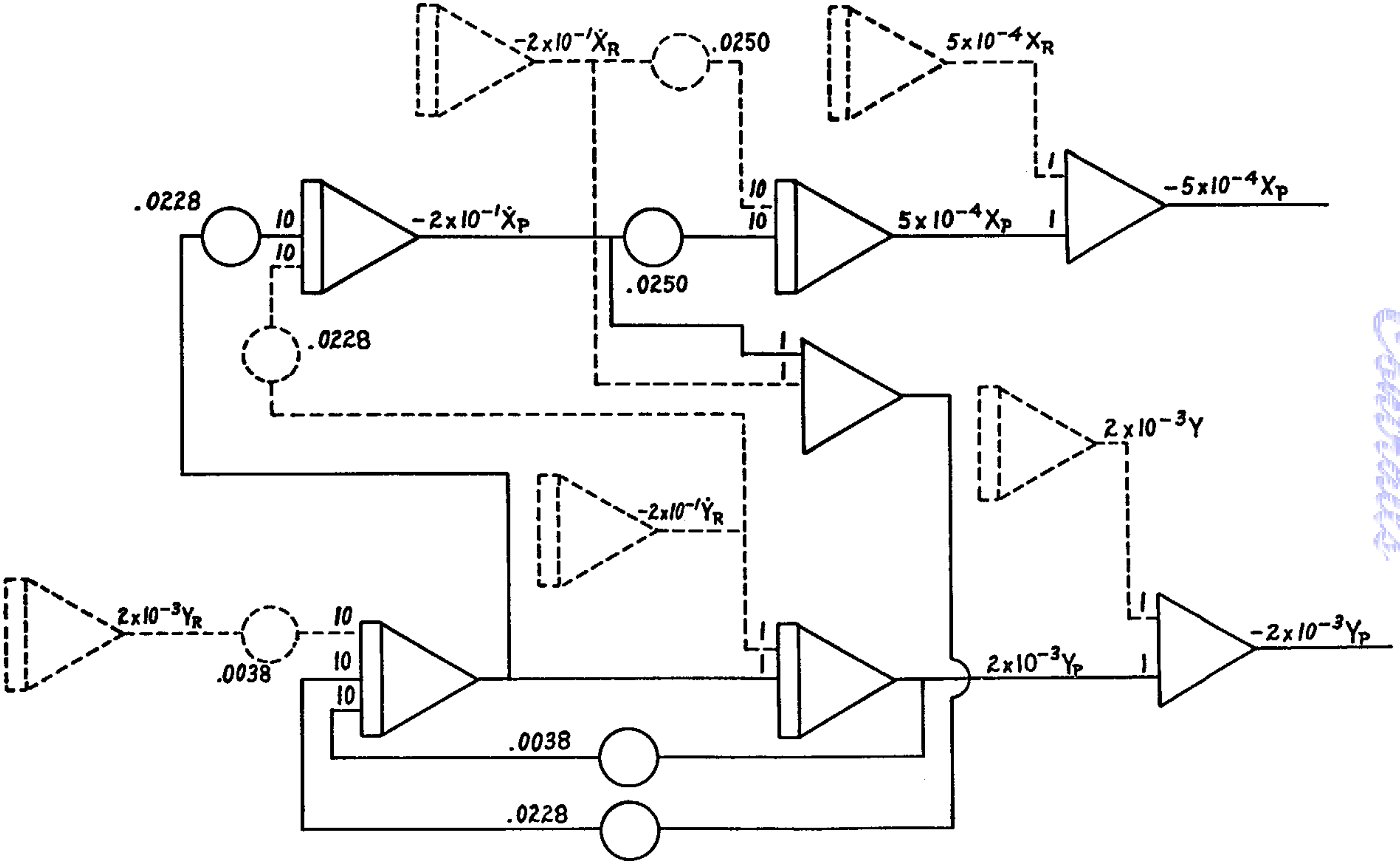

Figure C. Predictor (fast time) circuit.

| POT | SETTING | FUNCTION |
|---|---|---|
| 100 | .5000 | LIMIT |
| 101 | .5000 | LIMIT |
| 38 | .0100 | COMPUTE PERIOD |
| 39 | .2000 | RESET PERIOD |

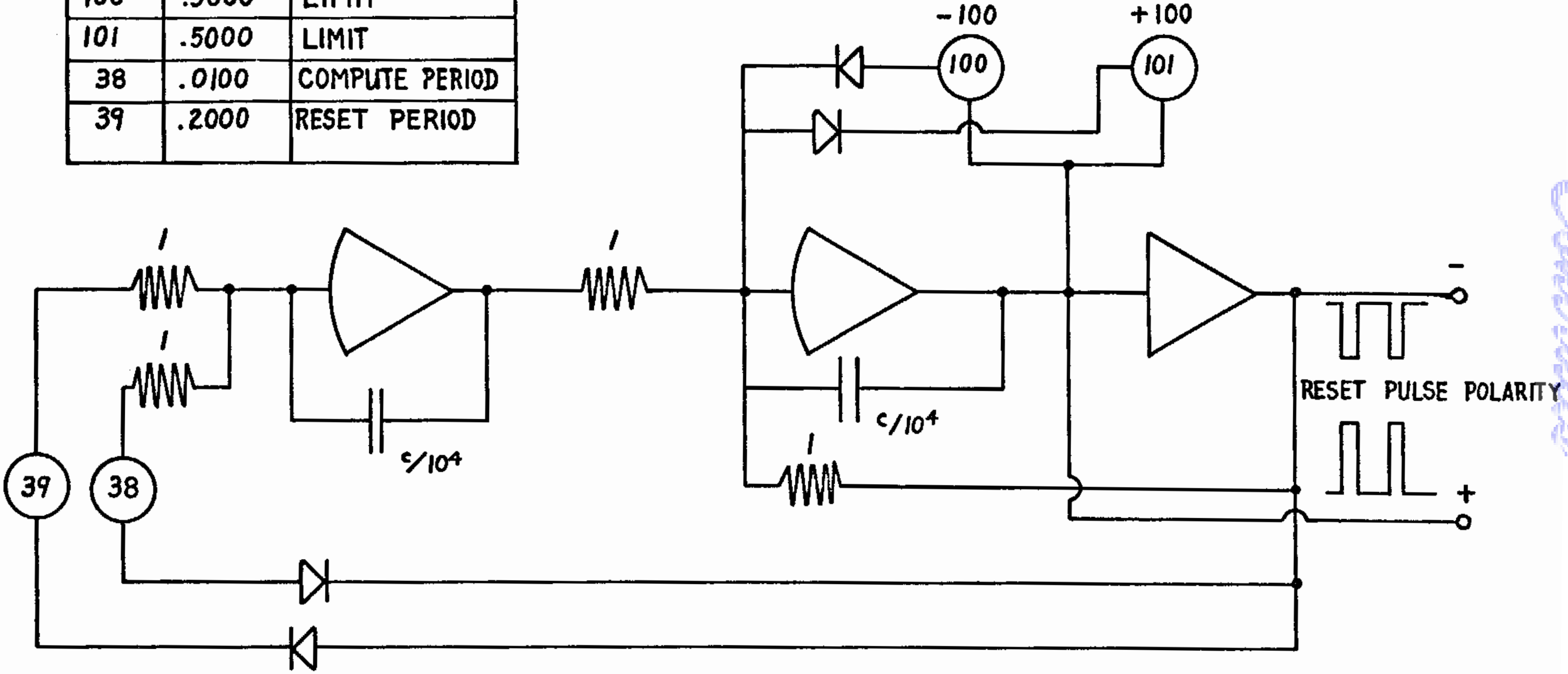

Figure D. Reset timing pulse generator.

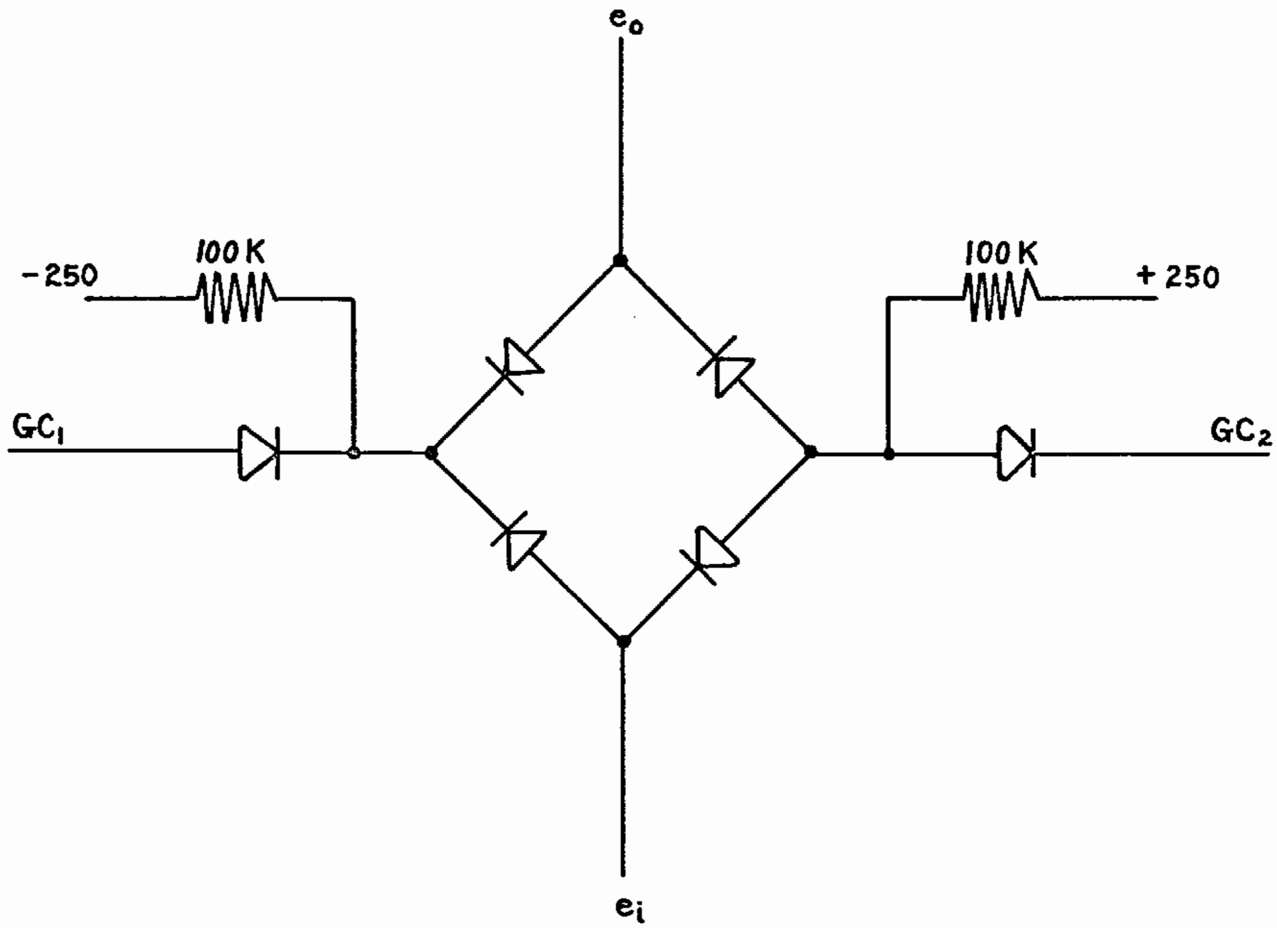

Figure E. Gate.

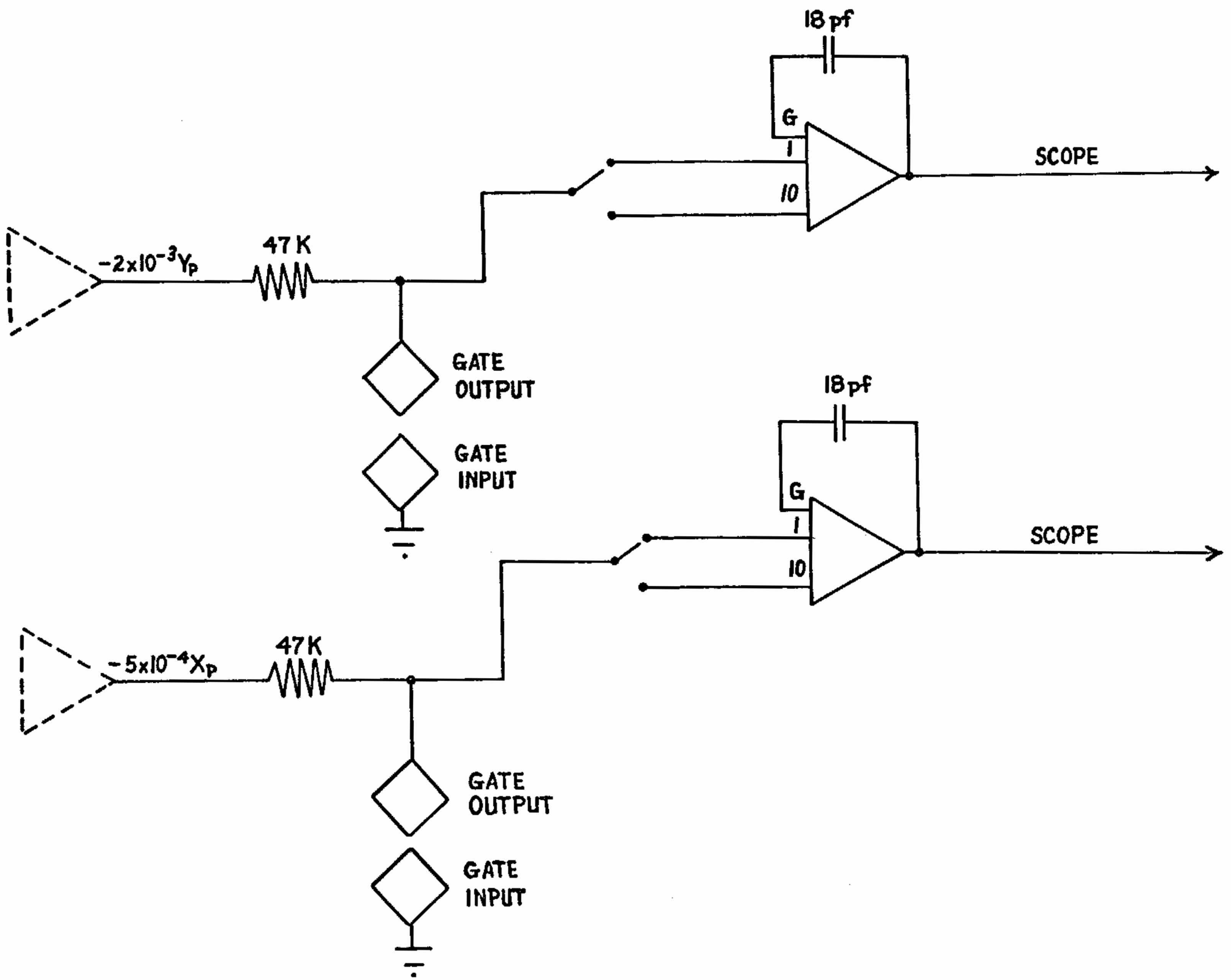

Figure F. Scale change circuit.

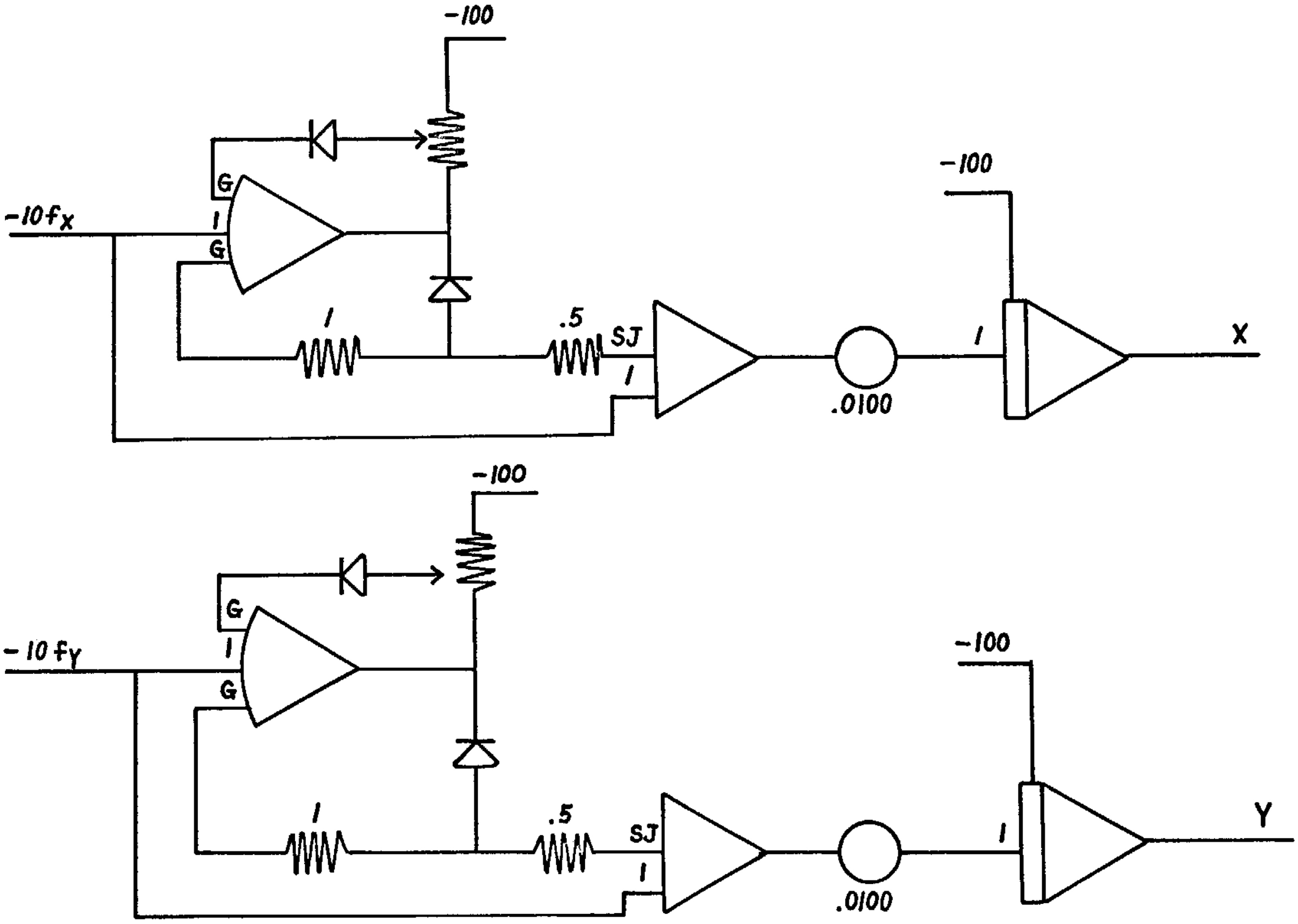

Figure G. Scoring circuit.

# APPENDIX II

## INSTRUCTIONS TO THE SUBJECT

You are going to participate in a study investigating a display concept for orbital rendezvous. Before describing your task in detail we want to acquaint you with some orbital dynamics.

See Figure 1.

The first figure shows a space vehicle in orbit around the earth. Orbit 1 is a circular orbit. If a retrograde or slowing down thrust is applied as shown in the figure, elliptical trajectories result. Orbit 2 is such an ellipse. As the vehicle falls toward the earth it gains velocity. The increase in velocity is sufficient to cause it to regain altitude, but as it climbs it slows down again resulting in the elliptic path. Orbit 3 results from enough deceleration to cause the vehicle to re-enter the atmosphere before regaining sufficient velocity to climb.

Now look at the second figure. Orbit 1 is again a circular orbit. The thrust applied as shown would cause the vehicle to accelerate and move into orbit 2. This orbit is also an ellipse, since as the vehicle gains altitude, it slows down and begins to fall. As the vehicle falls it gains velocity and begins to climb as in the first case. If a second thrust is applied at the highest point in the orbit (apogee), shown by the dotted line, orbit 3 is attained. This is a circular orbit higher than orbit 1. This is the most efficient way to change orbits. Thrust is used only twice, the remainder of the time is spent coasting. Similar two-impulse transfers exist for any orbit change.

The purpose of these figures is to show what happens when thrust is applied to an orbiting vehicle. Any questions?

Now look at figure 3a. The circle with the cross in it represents a vehicle in a circular orbit around the earth. Part of the earth can be seen below the vehicle. The figure is now centered on the vehicle and referenced to an imaginary line between the vehicle and the center of the earth. Thus the earth would appear to turn under the vehicle instead of the vehicle turning about the earth. The situation is exactly the same in Figures 1 and 2, only the view is changed. Figure 3b is a magnified view of the situation shown in 3a (only that part included in the dotted box). This dotted box surrounds the area of interest for one type of rendezvous. That is the area ahead of and above and below the target vehicle.

See Figure 3c.

Consider the path of a second vehicle attempting to rendezvous with the target vehicle. If the second vehicle is initially directly ahead of the target at the same altitude and speed (shown in Figure 3c) it must slow down to allow the target to catch up. If the interceptor simply slows up he will lose altitude and follow path 1. This path obviously will not allow him to rendezvous with the target. He must thrust upward to maintain his altitude at the same time that he slows down. If the proper combination of thrusts are applied he might follow path 2. All that would remain for him to do would be to accelerate to the same velocity as the target so that at intercept they would have no (zero) relative velocity.

Now look at the predictor display on this cathode ray tube. It shows you the interceptor's predicted path for a five minute period. The right hand end of the trace represents the interceptor's present position. The left hand end represents the interceptor's position five minutes in the future. This trace always represents a five minute prediction. As you accelerate and decelerate the trace will appropriately lengthen and shorten. If the interceptor is stopped relative to the target, the trace will become a dot. The curvature of the trace results from the orbital dynamics, discussed above, operating on the interceptor's velocity vector.

The dot on the left represents the target vehicle. At the start of each rendezvous maneuver your interceptor will be 80,000 feet ahead and 20,000 feet above the target. The scale on the display is 1 inch = 10,000 feet. Your task is to rendezvous with the target within 15 minutes using as little fuel as possible.

At the beginning of each run the initial impulse of a two-impulse transfer has been initiated but not so you will coast along the best trajectory. Your job is to correct the orbital path with this controller and continue to "fly" to the target and stop the interceptor at the target. This control stick is arranged so that you displace the stick in the direction you want the interceptor to accelerate. The more the stick is displaced the more thrust that is applied. To aid you in stopping at the target we will expand the scale when you get close to the target. When you reach a range of 10,000 (1 inch from the target) the scale will be expanded to 1 inch = 1,000 feet.

Fly the interceptor to the target, until the dots touch, then stop the interceptor. Remember use as little as fuel as possible and make your rendezvous within 15 minutes.

You will perform rendezvous maneuvers under two display conditions: (1) with predicted path, as I described above and (2) without predicted path. This second display condition will not have the trace representing the predicted path of the interceptor. You will receive 12 trials under each display condition. Any questions?

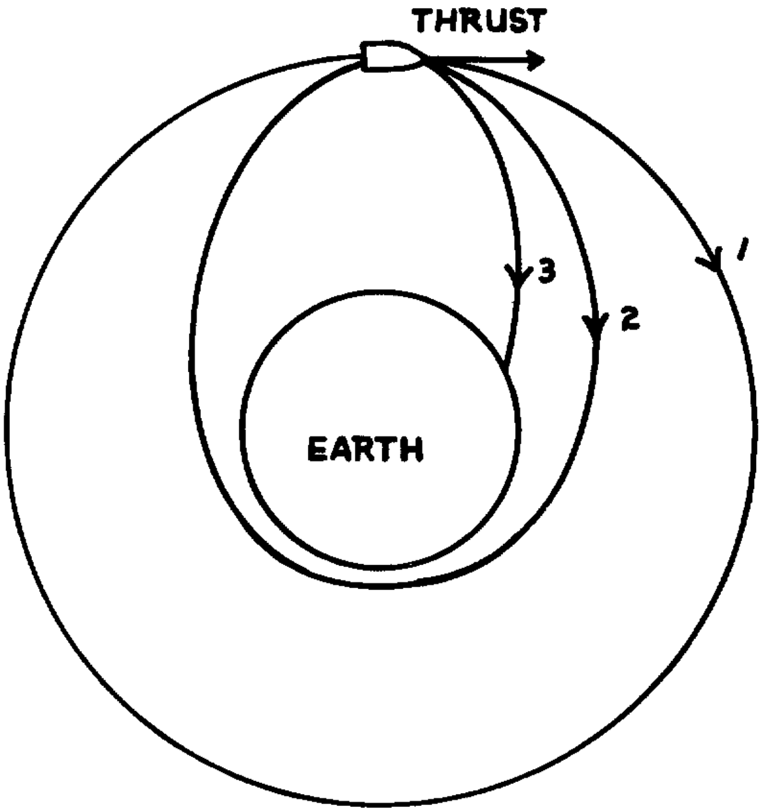

Figure 1

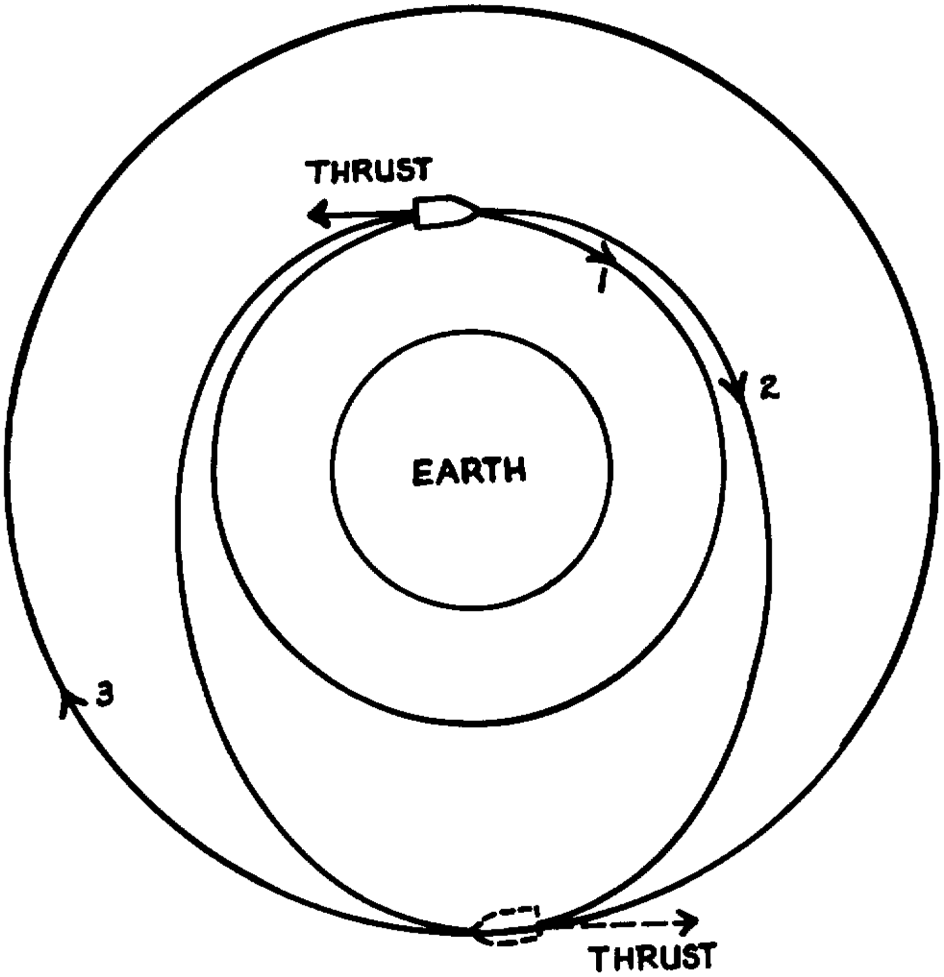

Figure 2

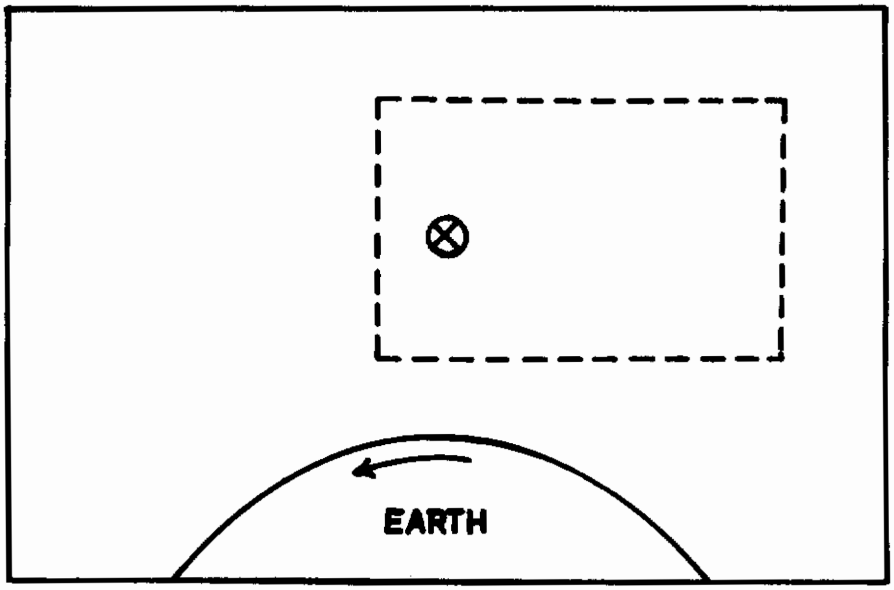

Figure 3a

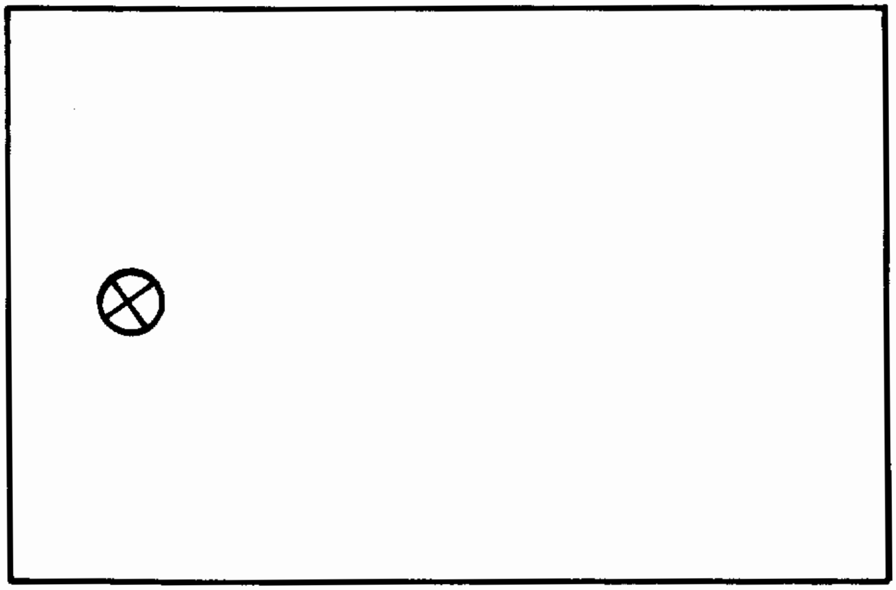

Figure 3b

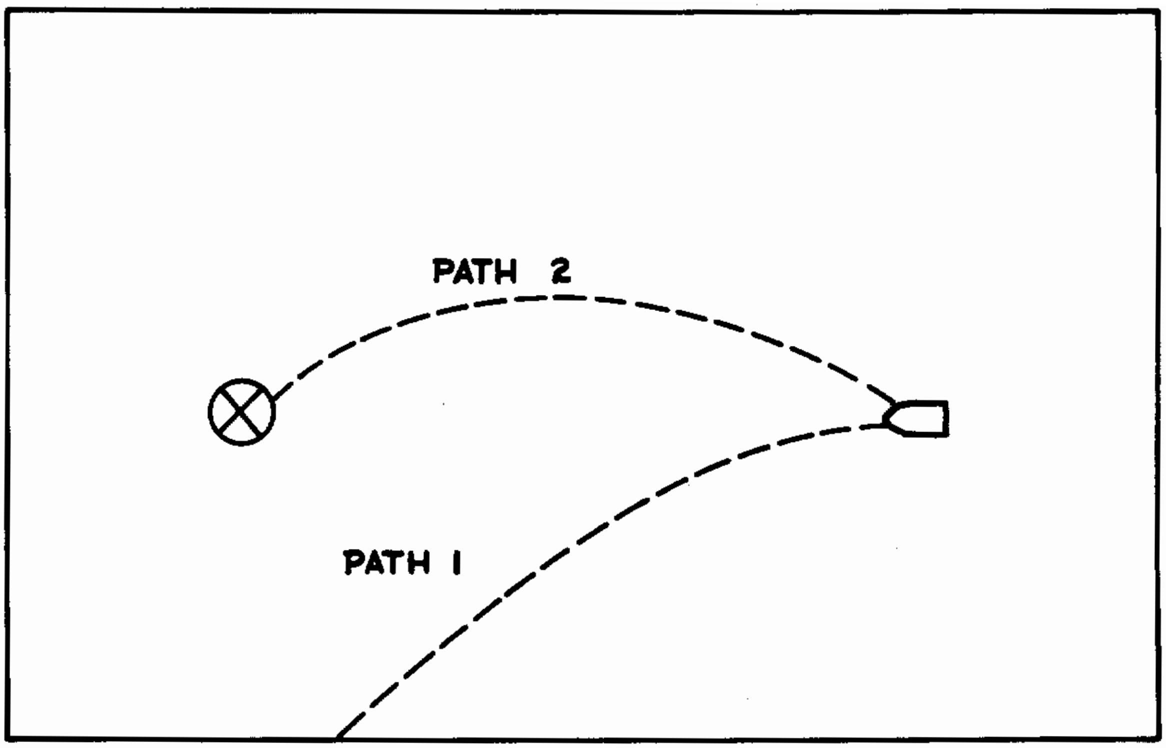

Figure 3c

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2. Mueller, D. D. Relative motion in the docking phase of orbital rendezvous. AMRL-TDR-62-124 (AD402384), Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, December 1962.

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| 14. KEY WORDS | LINK A |  | LINK B |  | LINK C |  |
|---|---|---|---|---|---|---|
|  | ROLE | WT | ROLE | WT | ROLE | WT |
| Prediction display system |  |  |  |  |  |  |
| Analog computer |  |  |  |  |  |  |
| Velocity |  |  |  |  |  |  |
| Interceptor spacecraft |  |  |  |  |  |  |
| Interception |  |  |  |  |  |  |
| Rendezvous trajectories |  |  |  |  |  |  |
| Orbital trajectories |  |  |  |  |  |  |
| Lunar landings |  |  |  |  |  |  |
| Operators (personnel) |  |  |  |  |  |  |
| Performance (human) |  |  |  |  |  |  |
| Time history |  |  |  |  |  |  |

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