PREDICTOR DISPLAY TECHNIQUES FOR ON-BOARD TRAJECTORY OPTIMIZATION OF RENDEZVOUS MANEUVERS

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FOREWORD

The study was a joint effort undertaken by Ritchie, Inc., Dayton, Ohio, working under Contract AF33(615)-2353, and the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories. Research was performed under 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 display format was conceived and developed by A. G. Berbert, Jr. of Ritchie, Inc. and G. G. Frost of AMRL.

This phase of the program was begun in December 1964 and was completed in November 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

Predictor displays for orbital rendezvous present to the pilot target position, interceptor position, and a continuous prediction of the interceptor trajectory relative to the target. Two experiments using rendezvous predictor displays are reported: (1) a comparison of on-line and off-line predictor techniques, and (2) a comparison of intermittent versus continuous updating of the prediction. All conditions tested yielded successful rendezvous performance. Off-line prediction, where the pilot could, at will, interrogate the predictor without expending fuel, was demonstrated to be significantly better than on-line prediction where the pilot could see only his actual predicted path. Intermittent updating produced no significant degradation of performance with update rates as low as once per 50 seconds.

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SECTION I

INTRODUCTION

Manual control of an orbital rendezvous maneuver presents a difficult task to an astronaut. While the equations of motion of orbital bodies are not extremely complex, particularly if certain assumptions (such as a spherical earth) are made, the relative motion between two orbiting bodies is still rather difficult to visualize. In orbit, particularly with the low thrust levels currently available for maneuvering, things happen slowly. It is difficult to determine immediately, the effect of a small velocity change. Discrete thrusts result in curved orbital paths and changing velocity relative to the target vehicle. This makes visualizing the orbital motion and determining the rate of closure with the target vehicle very difficult if only extravehicular visual cues are available.

A program was initiated to investigate the use of fast-time modeling, well known in engineering design practice, to generate a display for manual control of rendezvous maneuvers. This display, driven by a fast-time repetitive computer, shows the pilot his predicted trajectory, relative to the target, based on some given control action.[1]

Earlier work in applying predictor techniques to rendezvous problems (ref 1, 2) indicated that the technique was potentially a valuable aid to an operator performing rendezvous maneuvers.

The following sections describe a simulation program designed to evolve a refined predictor display for on-board trajectory optimization in a Gemini-type rendezvous maneuver. Two studies are reported: (1) a comparison of on-line and off-line prediction, and (2) a study of the effects of intermittent updating of the predictor model.

SECTION II

RENDEZVOUS PROBLEM

The rendezvous problem studied was similar to the terminal phase of a Gemini-Agena type maneuver. The initial line-of-sight (LOS) ranges were approximately 50

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[1] Early work in the development of the Predictor Concept was done by Dr. Charles R. Kelley, of Dunlap and Associates.

nautical miles. Two starting positions and four sets of initial rates were investigated. The target-centered coordinate system used to define the rendezvous maneuvers is shown in figure 1. The initial conditions (IC) are shown in table I.

TABLE I
INITIAL CONDITIONS

IC	x range	y range	x rate	y rate
1	-278,500 ft	-119,710 ft	250.4 ft/sec	0 ft/sec
2	-278,500 ft	-119,710 ft	225.5 ft/sec	37.5 ft/sec
3	-278,500 ft	-119,710 ft	250.4 ft/sec	-10.0 ft/sec
4	-278,500 ft	+ 20,000 ft	-35.0 ft/sec	- 8.5 ft/sec

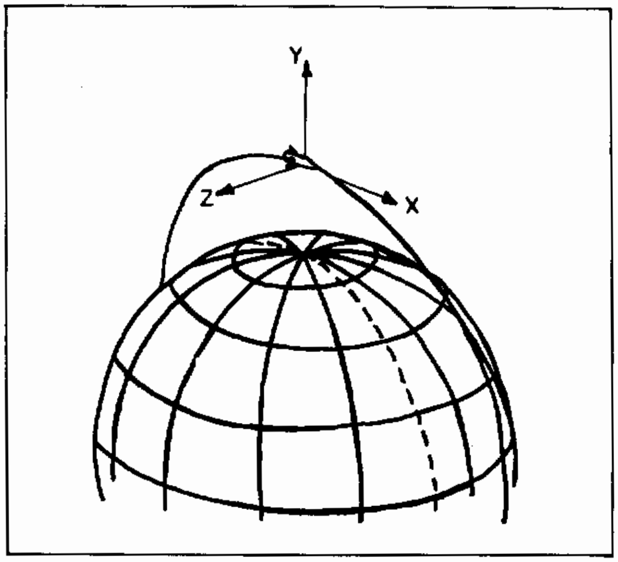


Figure 1. Coordinate System

Figure 2 (a and b) shows how a target centered coordinate system transforms a trajectory given in an inertial coordinate system. Figure 2a shows a target vehicle in a circular orbit with the interceptor in an elliptical orbit. The figure has been exaggerated for clarity. Note the positions marked 1 through 9 which indicate where, on their respective trajectories, the target and the interceptor are at 9 different times. Figure 2b illustrates the relative motion trajectory of the vehicles shown in figure 2a. The target is held at zero position in the rotating coordinate system and the interceptor's position is shown relative to the target.

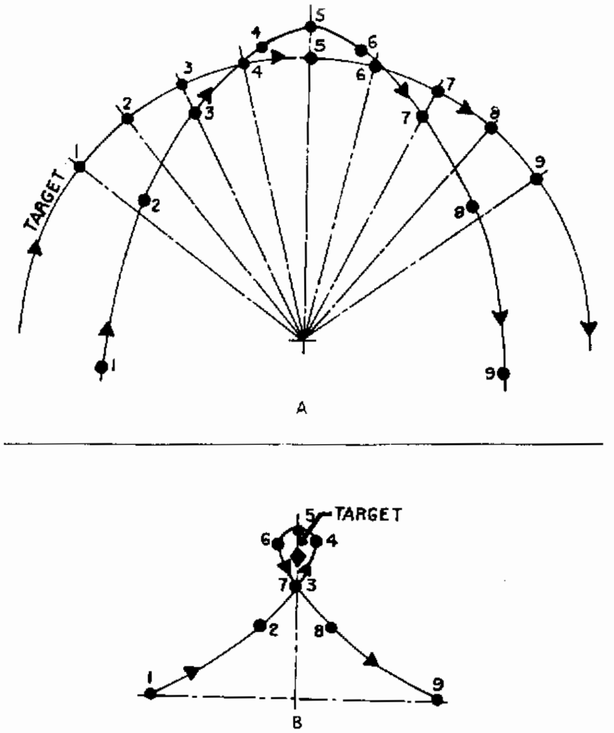
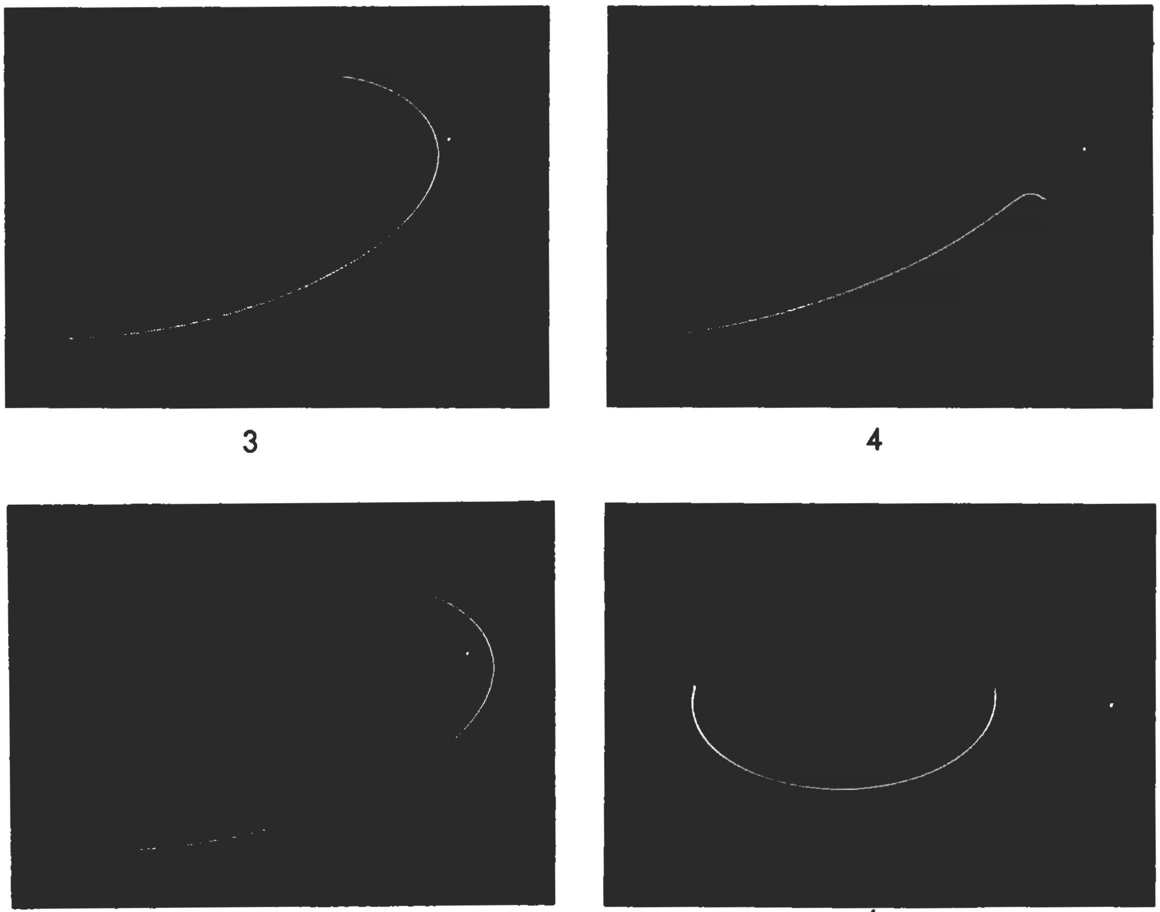


Figure 2. Transformation from Inertial to Target Centered Coordinate Systems.

Figures 3 through 6 show the resulting predicted relative motion for IC 1 through 4 respectively.

A minimum fuel rendezvous maneuver, given the IC, can be accomplished by thrusting at some angle relative to the target vehicle to establish an intercept course, coasting to the target, then applying a second thrust to match velocities with the target vehicle (two-impulse orbital transfer). This orbital transfer technique results in the interceptor translating along a curved trajectory and changing velocity relative to the target.

Kasten (ref 3) and Clark (ref 4) among others, have demonstrated that two-impulse techniques, or a combination of two-impulse and line-of-sight (LOS) techniques are possible but difficult for the operator to perform with only extravehicular visual cues (actually simulated symbolic cues representing the "real world"). Usually the operators resort to multi-impulse inputs to correct trajectory errors, which results in the interceptor approaching the target more or less along the LOS. Mueller (ref 5) shows that for rendezvous times beyond 5 minutes a LOS transfer requires significantly more fuel (velocity change) than a two-impulse transfer to complete a rendezvous. Figure 7 shows the ratio of fuel required to effect an LOS rendezvous to the fuel required for a two-impulse rendezvous as a function of time to rendezvous.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Figures 3 - 6. Display of IC 1 thru 4 Before Correction.

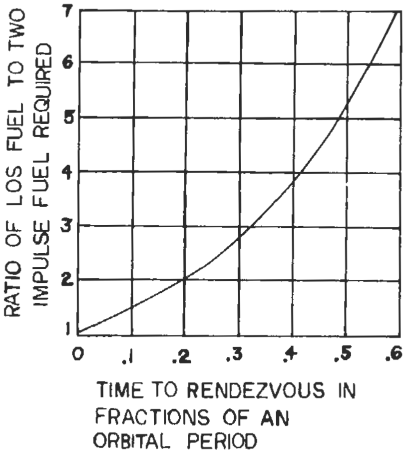


Figure 7. Relative Fuel Expenditure for Two-Impulse and LOS Orbital Transfers.

With training, an operator can learn orbital mechanics so that at short ranges he can establish a collision course and decelerate to stop in the vicinity of the target given only a relative position shown on a side-looking profile display (ref 1). Fuel expenditure (ΔV) when given only this information, was high compared to maneuvers when predicted path was displayed (ref 2).

ON-LINE PREDICTION

The predictor display concept facilitates two-impulse transfer techniques because the relative trajectory is displayed to the operator. He can tell, within the accuracy of the scale on the display, where the interceptor's curved path is taking him relative to the target. Since the end-point of the predicted trajectory always represents the operator's position a known constant time into the future, he can estimate when he will reach the target. His task initially, then, is to thrust so that the interceptor's predicted path hits the target. Figures 8 through 11 show the predicted paths for IC 1 through 4 respectively, after the initial course correction. Once on a collision course, the operator's task is to determine what inputs will stop the interceptor at the target (match velocities). Thrust inputs that reduce the length of the predicted path indicating reduced velocity without moving the path off the target are desired here. Figure 12 shows such a deceleration maneuver for IC 1.

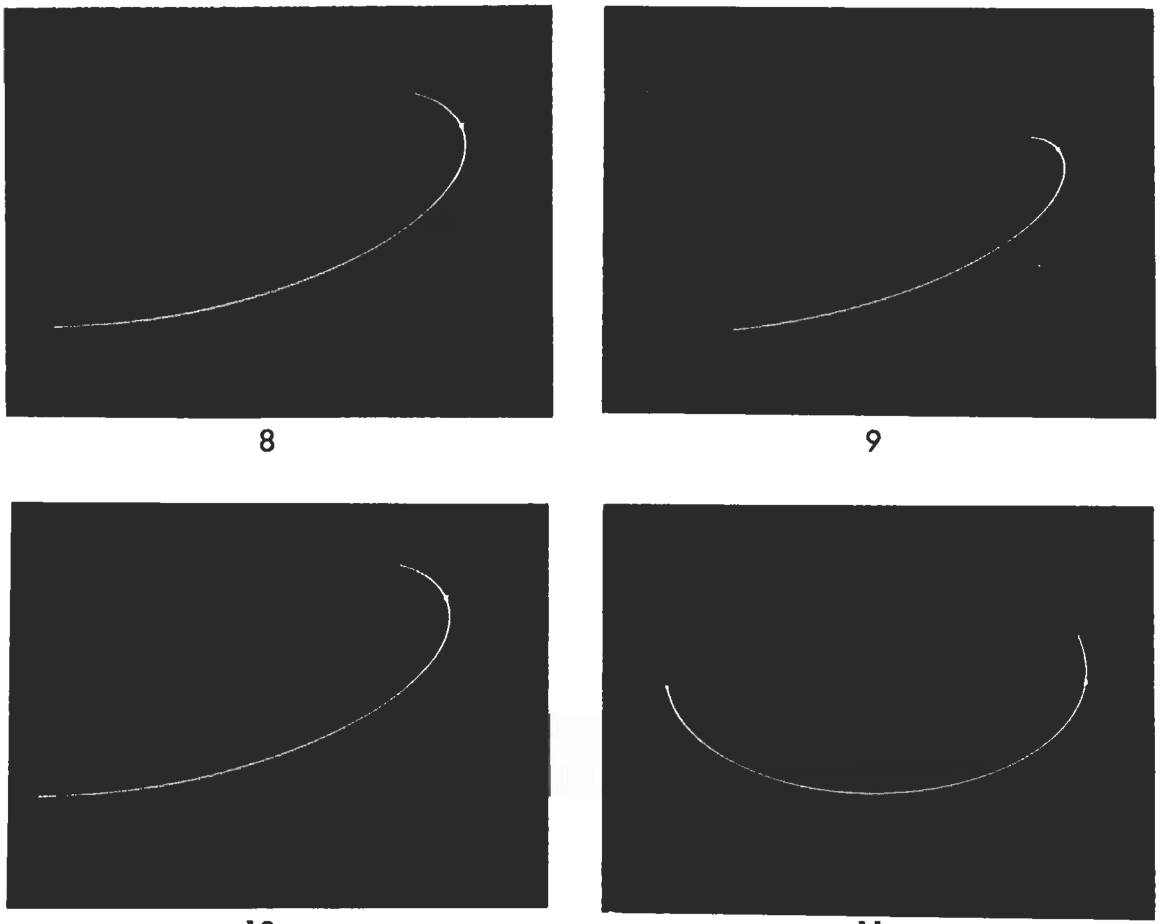
OFF-LINE PREDICTOR

A refinement in predictor techniques for orbital rendezvous utilizes off-line (or trial) prediction. Off-line prediction allows the operator to select a trial pitch attitude and a trial thrust duration (at fixed level) and discover how these selected inputs would affect the interceptor's path relative to the target without actually applying thrust to the vehicle. These trial inputs, tested on the fast-time (predictor) circuits, do not affect the real vehicle. Such a technique can be used for both establishing a collision course with the target and for matching velocities with the target when the range is low. Analytically it appeared that such a technique would be useful in aiding the operator to determine the fuel-time trade-offs and to select the most desirable trajectory. The comparative study described below tested this hypothesis.

SECTION III

SIMULATION

For simplicity of mechanization a target-centered, earth oriented coordinate system was chosen (shown in figure 1).



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Figures 8 - 11. Display of IC 1 thru 4 after Correction.

Figure 12. Display of IC 1 after Deceleration.

The equations of relative motion used in the rendezvous simulation are from Mueller (ref 5) and are as follows:

$$\ddot{x} = f_x - 2\,\omega\dot{y}$$

$$\ddot{y} = f_y + 2\,\omega\dot{x} + 3\,\omega^2\,y$$

$$\ddot{z} = f_z - \omega^2\,z$$

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 (thrust per unit mass on the interceptor exclusive of gravity)
$\dot{x}$, $\dot{y}$ and $\dot{z}$ = x, y, and z velocities of the interceptor
ω = angular velocity of the rotating coordinate system relative to inertial space.

The target was assumed to be in a circular orbit (165NM). The target's orbit and the interceptor's orbit were assumed to be coplanar ($z = \dot{z} = 0$), thus only the equations for $\ddot{x}$ and $\ddot{y}$ were programmed.

An analog computer was programmed to provide the real-time dynamics, the fast-time solutions and an idealized pitch-thrust translation control system (circuit diagrams are shown in appendix 1). No thruster dynamics were included in the attitude control system. Pitch attitude relative to the target was displayed on a 5in. cathode ray tube (CRT) and an on-off control (button) was used for applying thrust (0.5 ft/sec^2). Pitch rotation was unlimited.

The off-line predictor was mechanized using two potentiometers, one for pitch attitude and one for thrust level, and an activate switch. (The circuit diagram is shown in appendix 1.) The potentiometers controlled voltages scaled appropriately to represent a pitch attitude and thrust level (ΔV in ft/sec). When the activate switch was pushed these voltages were added into the fast-time circuits. The resulting changes in the predicted path display indicated how the selected pitch attitude and thrust level would change the current orbital path if these velocity changes could be made instantaneously.

The predicted relative trajectory was displayed on a 21 in. CRT in the on-line vs off-line comparison study. The display scale was 1 inch equals 20,000 ft. Figure 13 shows the operator station which includes the display, the real-time control system and the trial predictor controls.

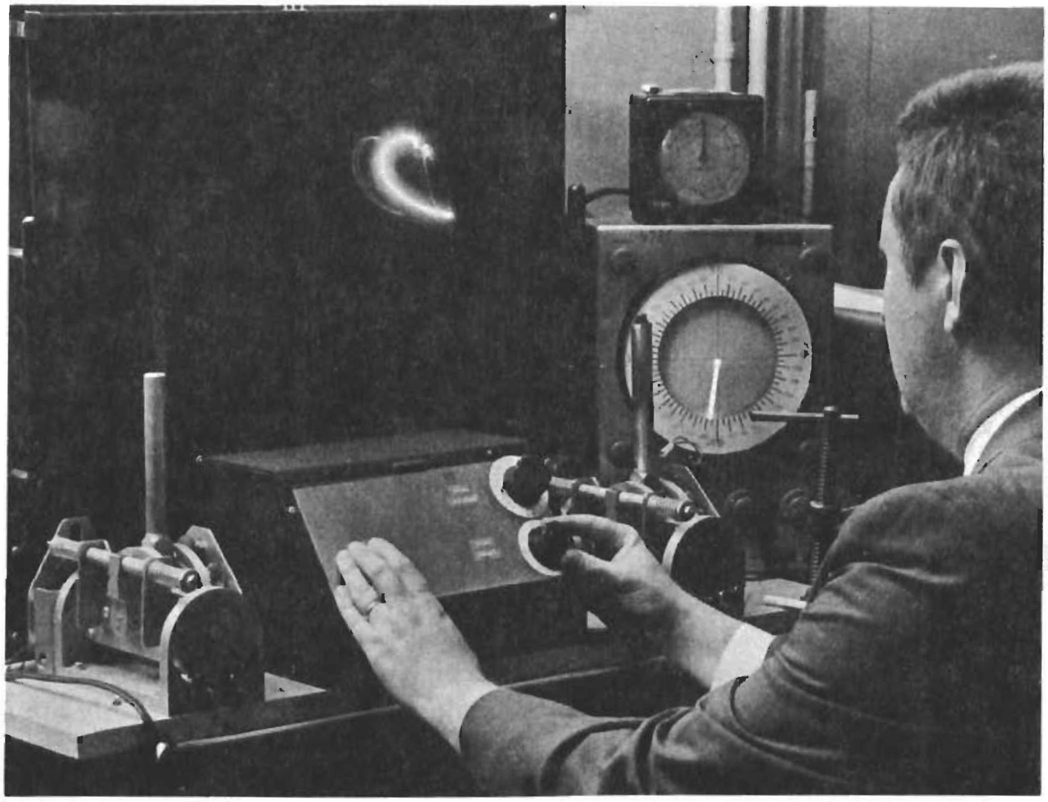

Figure 13. Operator's Station.

The initial ranges and velocities shown in table 1 required approximately 37-40 minutes for the interceptor to reach the vicinity of the target if no acceleration thrusts were applied. Longer times are involved when the interceptor must match velocities, since decelerating relative to the target slowed down the approach thus increasing total run time (approximately 55 - 60 minutes). These times also depend on the thrust level available and the time-fuel tradeoffs made by the operator. In any case, these problem times would have severely constrained number of runs per subject for the planned studies as well as requiring impossible accuracy from the analog computer. For these reasons the simulated problem was time scaled to run at twice real-time speed; that is, the entire maneuver required from 25 to 30 minutes.

The rendezvous task involved discrete control inputs, and even with the accelerated time scale, there were several minutes between control inputs. We assumed that if the subject-operators could successfully perform rendezvous maneuvers with the acclerated time scale, they could successfully perform in real-time.

Given a set of initial conditions (x and y positions and rates) digital solutions were obtained to serve as reference trajectories to tune the analog simulation. Tedious adjustment of potentiometers and judicious selection of scale factors were required to obtain reasonably accurate (less than 0.5% error in range compared to the digital solution) problem runs.

SECTION IV

COMPARISON OF ON-LINE AND OFF-LINE PREDICTION

The first study accomplished after the above described simulation was mechanized, was a comparative evaluation of operator performance of rendezvous using on-line and off-line predictor techniques.

METHOD

Twelve university students were originally scheduled in a treatment x subjects experimental design to allow comparisons between on-line and off-line display systems. The four IC shown in table I were used, with each subject receiving two IC during training and two IC for a criterion test. Six subjects were lost due to scheduling problems half way through the program. The remaining subjects were given a total of 16 training runs (4 on-line and 4 off-line trials on each of the two IC) after a 30-minute briefing on orbital mechanics and a description of the task. Instructions to the subjects are in appendix II. Following the training runs, each subject received 2 runs on each of the remaining IC, 1 run with off-line prediction and 1 run with on-line prediction. The order of presentation of the IC and display conditions was counterbalanced, for both the training and test trials.

OPERATOR'S TASK

A successful rendezvous was defined as one in which range and range rate were brought to 1000 feet and 10 ft/sec respectively, within 30 minutes.[1] Comparator circuits were implemented so that when a subject achieved criterion range and range rate the problem automatically went into "Hold." Subjects were told to use as little fuel for translation and attitude change as possible but to achieve rendezvous within the time limit. A clock was provided so the subject could monitor time. Subjects

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[1] The reader should remember that this corresponds to sixty minutes of "real time" because of the time scaling mentioned earlier.

were told the amount of fuel (velocity increment[1] and degrees of rotation) they had expended at the end of each run.

RECORDED DATA

To evaluate operator efficiency at performing rendezvous the following data were recorded:

1. ΔV (velocity increment) to complete a rendezvous.
2. Time history of thrust control.
3. x-y plots of the trajectory flown.
4. $\Delta\theta$ (pitch attitude change in degrees).
5. Time to rendezvous.

RESULTS AND DISCUSSION

Training Trials

Table II shows the ΔV's (for translation) and time to rendezvous for the last two trials on each IC given in the training session. Clearly, less fuel was used when off-line prediction was used. A Wilcoxin Matched Pair Signed Ranks Test (ref 6) indicated the difference was significant ($P < .01$). Averaging ΔV scores across subjects for each IC indicated that off-line prediction reduced fuel consumption (ΔV) from 16% to 30% depending on the IC.

Figures 14 through 17 show the calculated theoretical minimum ΔV's[2] and obtained ΔV's as a function of time to rendezvous. Note that the lower ΔV's obtained with off-line prediction were not consistently closer to the theoretical minimum than ΔV's obtained with on-line prediction. This was due to the variance in time to rendezvous. Subjects were not informed of the shape of the minimum fuel vs. time to rendezvous curve or how it varied with each IC. The only feedback they received was fuel consumed (both

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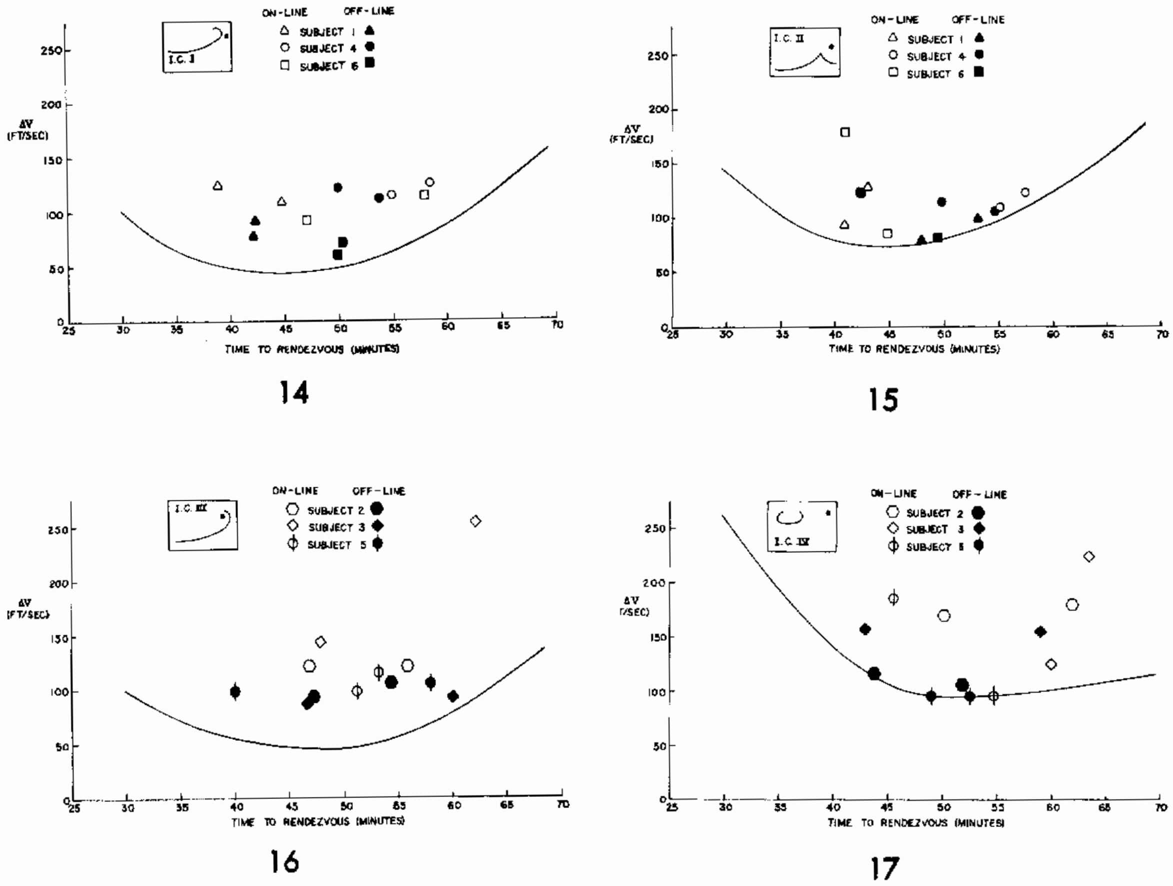
[1] ΔV is proportional to fuel expended and can be calculated if vehicle mass and specific impulse of fuel are known.

[2] The method of calculating therortical minimum ΔV's is shown in appendix III.



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Figures 14 - 17. Minimum and Obtained ΔV vs Time to Rendezvous - Training Trials.

Test Trials

Table III shows the obtained ΔV (translation) and time to rendezvous, for each subject on one run on each of two unfamiliar IC. Again, more fuel was used in the on-line prediction trials. A Wilcoxin Matched Pair Signed Ranks Test indicated the differences were significant ($P < .01$).

Averaging ΔV scores across subjects for each IC indicated that off-line prediction reduced fuel consumption (ΔV) from 7% to 24%, depending on the IC, from that obtained with on-line prediction.

Figures 18 through 21 present the obtained ΔV's and the calculated theoretical minimum ΔV as a function of time to rendezvous for each IC. As before, the lower ΔV's obtained with off-line prediction are not consistently closer to the theoretical

TABLE II

TRAINING TRIALS ΔV AND TIME FOR LAST TWO TRIALS ON EACH IC UNDER EACH DISPLAY CONDITION FOR EACH SUBJECT.

		On-Line				Off-Line			
Subject	IC	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)
1	1	133	49.1	110	45.0	78	42.3	90	42.4
	2	96	40.7	130	42.8	109	53.3	83	48.6
2	3	121	56.1	122	47.5	108	54.4	94	47.6
	4	179	62.1	177	50.4	112	52.8	116	44.0
3	3	147	48.8	256	60.4	95	60.0	91	47.0
	4	224	63.5	127	60.4	157	59.0	160	43.3
4	1	107	57.8	102	59.0	116	42.8	91	42.4
	2	124	55.1	126	57.4	118	50.3	116	57.8
5	3	117	53.2	98	51.2	106	58.4	101	40.4
	4	187	45.6	99	54.8	99	52.6	98	49.2
6	1	89	47.2	115	57.0	60	50.2	70	50.4
	2	184	40.8	85	45.4	124	42.7	84	49.4

attitude and translation) and time elapsed for each run. Subjects did not attempt to achieve a particular time to rendezvous, except to complete the maneuver within the time limit. It was hypothesized that knowledge of the fuel vs time to rendezvous curve for each IC would have aided the subjects in getting closer to the theoretical minimum.

Δθ for Training Trials

An undetected malfunction in the scoring circuit for Δθ yielded unreliable scores, so no analysis was done.

TABLE III

TEST TRIALS, ΔV AND TIME FOR EACH IC AND DISPLAY CONDITION.

		On-Line		Off-Line	
Subject	IC	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)
1	3	102	42.8	100	56.4
	4	137	52.4	111	56.8
2	1	155	52.4	137	58.4
	2	143	50.1	121	92.5
3	1	89	44.8	80	40.6
	2	184	66.2	168	52.6
4	3	96	41.1	94	60.0
	4	136	55.8	126	56.8
5	1	78	56.9	74	48.4
	2	134	60.8	119	49.6
6	3	114	37.6	83	50.2
	4	210	66.9	118	40.8

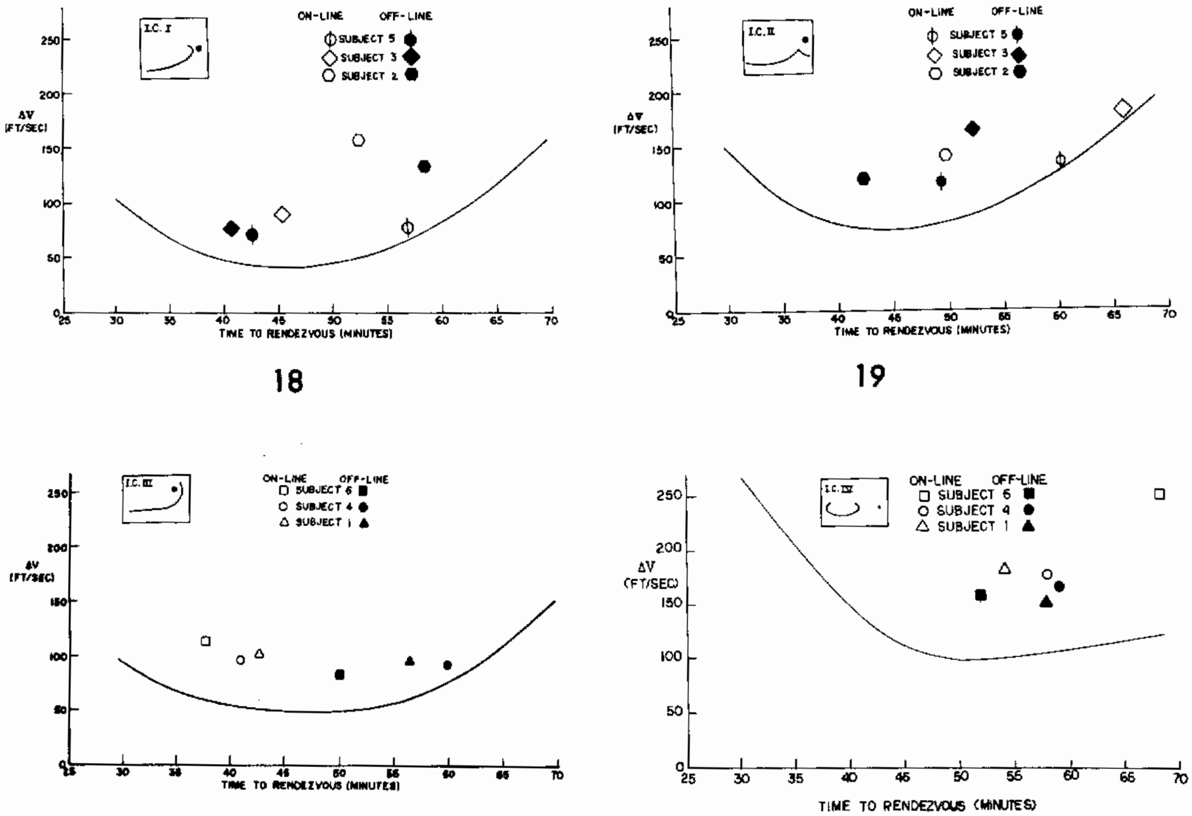
minimum than ΔV's achieved with on-line prediction. As before, this was attributed to varience in the times to rendezvous obtained for each IC.

Δθ For Test Trials

Table IV shows the Δθ's for each run by each subject for the unfamiliar IC. Less rotation of the vehicle was required when off-line prediction was used. A Wilcoxin Matched Pair Signed Ranks Test indicated the difference was significant ($P < .01$).

Control Strategy

It was pointed out earlier that the most efficient (in terms of fuel consumption) orbital transfer technique was a two impulse technique. If the operator could de-



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Figures 18 - 21. Minimum and Obtained ΔV vs Time to Rendezvous - Test Trials.

termine what course correction was required to intercept the target and what retro thrust input would match velocities with the target vehicle at close range, only two thrust inputs would be required.

Figure 22 shows the proportion of total thrust to complete a rendezvous in 2 minute intervals for off-line and on-line prediction. Examination of the time histories of thrust inputs revealed a marked difference in control strategy between on-line and off-line prediction techniques. The proportions are averaged across subjects. Clearly, off-line prediction yielded more efficient control in that the distribution of thrust inputs more closely approaches 2 impulses.

TABLE IV

TEST TRIALS, Δθ FOR EACH RUN ON EACH IC UNDER EACH DISPLAY CONDITION.

Subject	IC	On-Line Δθ (in degrees)	Off-Line Δθ (in degrees)
1	3	497	315
	4	326	399
2	1	525	539
	2	1176	749
3	1	420	406
	2	980	595
4	3	490	231
	4	1372	714
5	1	301	210
	2	273	420
6	3	686	175
	4	490	175

Trajectory Plots

Figure 23 shows representative trajectories flown on the same IC (IC 1) with both on-line and off-line prediction. No differences are detectable with the scale factors used. It can be noted however that both display conditions yeilded smooth trajectories to intercept.

SECTION V

EFFECT OF INTERMITTANT UPDATE OF THE PREDICTOR MODEL

The predictor model used in the first studies was essentially continuously updated. That is, on every computation cycle (70 milliseconds) the fast-time model received new initial conditions (real-time position and rate) from which to solve the equations for orbital path.

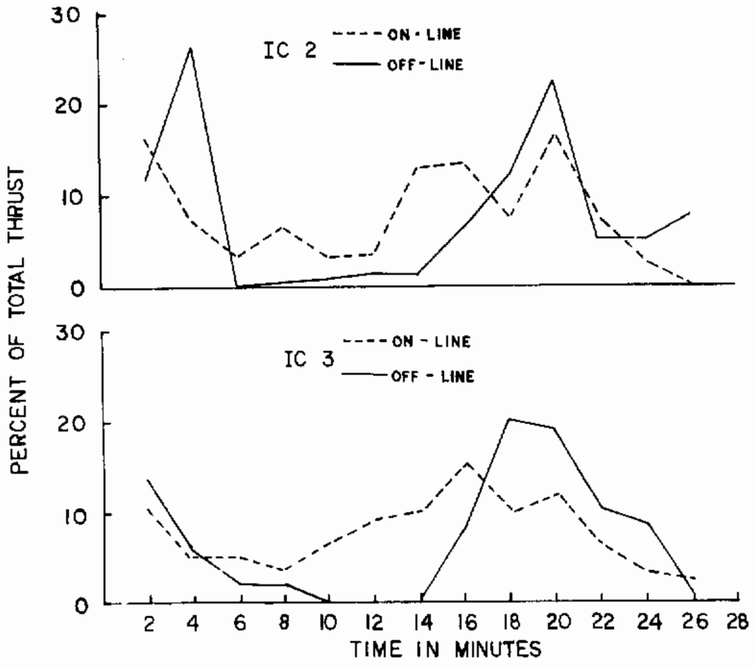


Figure 22. Percent of Total Thrust vs Time.

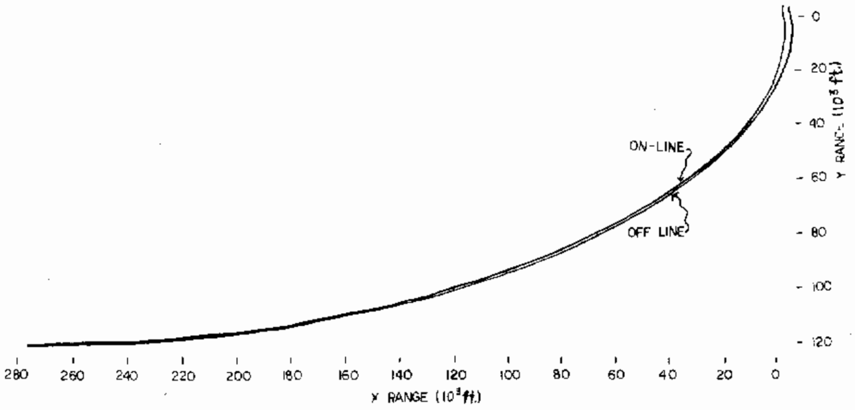


Figure 23. Trajectory Plots.

Available literature on a proposed rendezvous radar system indicated the position and rate information would not be available continuously for display purposes. The displays were to be updated in 50 to 100 sec intervals. This information led to a study to determine the effect of intermittant updating of the predictor model on operator performance of rendezvous.

Two modifications of the rendezvous simulation were accomplished before initiating this study. Sample and hold circuits were instrumented between the real-time circuits and the fast-time model to allow control of the rate at which the fast-time model received real-time position and velocity data. (Circuit diagram is in appendix I). Two relay timers were utilized to control update rates.

The second modification was to reduce the display size from a 21 in. CRT to a 5 in. display. A 21 in. rendezvous display hardly seemed feasible for operational use.

Three update rates were selected for the study: (1) continuous, (2) 25 seconds between updates, and (3) 50 seconds between updates. Remembering that the problem had been time scaled, these update rates corresponded to continuous, 50 seconds and 100 seconds in real-time.

METHOD

Eight university students were used in a treatment x subjects experimental design.

Subjects received a 30 minute briefing covering orbital mechanics and relative motion as well as the details of their control task. The same IC as in the first study were used. Each subject was trained on two of the four IC. Subjects received 12 training trials (two trials on each of the three update rates for each of the two IC). Then, each subject received 6 test trials on two unfamiliar IC. (one trial on each IC at each of the three update rates).

OPERATOR TASK

The same criteria for a successful rendezvous as in the first study were used. However, in this experiment subjects were shown the time to rendezvous vs ΔV curves for each IC to enable them to attempt a minimum fuel (ΔV) rendezvous given the IC.

MEASURES

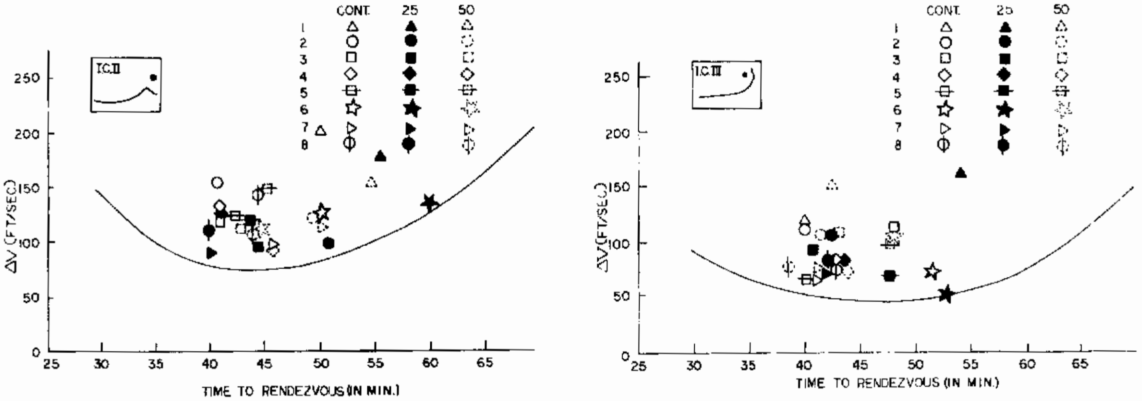
The same measures as in the first study were taken in this study. However, in order to increase the sensitivity of the trajectory plots to possible differences in smoothness of orbital path flown as a function of display conditions, only the last 100,000 ft of range was plotted.

RESULTS

ΔV and Δθ Scores

Table V shows the obtained ΔV scores (for translation) for each subject on the last trial for each IC in the training trials, as a function of update rate. There were no significant differences in ΔV as a function of update rate. A Rank Test for Matched Data (ref 6) indicated we could not reject the null hypotheses.

Figures 24 and 25 show the obtained ΔV scores for each update rate for each subject plotted with calculated theoretical minimum ΔV versus time to rendezvous. These figures indicate the general achievement level of the subjects and the relative effect of update rate. Update rate did not affect ΔV as shown above, and comparing figures 24 and 25 with figures 14 through 17 indicates that the subjects in the update study did not achieve better maneuvers (in terms of ΔV and time to rendezvous) than the subjects in the first experiment. Although the subjects in the update study were shown the ΔV versus time to rendezvous curves, they did not do noticeably better. The scale factor on the display of predicted orbital path was severely reduced for the update rate study (from 1 inch = 20,000 ft to 10 millimeters = 40,000 ft). Since both groups of subjects exhibited considerable variance in time to rendezvous, perhaps time to rendezvous should be explicitly displayed.



Figures 24 - 25. Minimum and Obtained ΔV vs Time to Rendezvous - Training Trials.

Table VI shows the obtained Δθ scores as a function of update rate for each trial shown in table IV. There is no significant difference in Δθ scores as a function of update rate. A Rank Test for Matched Data does not indicate rejecting the null hypotheses.

TABLE V

OBTAINED ΔV's AND TIMES TO RENDEZVOUS FOR EACH SUBJECT ON THE LAST TRIAL FOR EACH IC IN THE TRAINING TRIALS, AS A FUNCTION OF UPDATE RATE.

		Update Rate					
		Continuous		25 seconds		50 seconds	
Subject	IC	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)
1	2	200	50.0	175	56.1	150	55.1
	3	120	40.0	163	54.2	152	42.4
2	2	152	40.2	97	51.4	119	49.2
	3	117	40.1	110	42.1	110	42.1
3	2	120	41.7	92	44.8	115	42.5
	3	115	48.0	91	40.6	110	42.4
4	2	132	41.3	125	40.4	93	46.0
	3	88	42.6	90	42.4	80	42.4
5	2	123	42.4	117	43.4	145	46.3
	3	67	40.4	72	48.2	100	48.2
6	2	126	40.1	135	59.4	120	44.1
	3	77	51.8	82	52.4	105	97.1
7	2	95	46.8	92	40.2	112	50.4
	3	73	40.4	75	41.4	76	41.4
8	2	145	46.4	110	40.4	110	44.4
	3	80	42.4	85	42.4	87	38.2

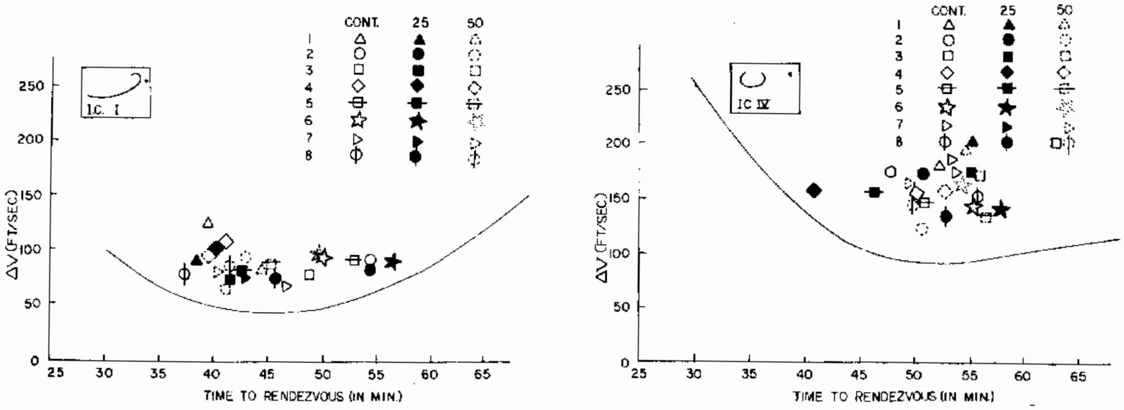
TABLE VI

OBTAINED Δθ FOR EACH SUBJECT ON THE LAST TRIAL WITH EACH IC IN THE TRAINING TASK, AS A FUNCTION OF UPDATE RATE.

Subject	IC	Update Rate Continuous Δθ (in degrees)	25 seconds Δθ (in degrees)	50 seconds Δθ (in degrees)
1	2	700	320	400
	3	220	700	750
2	2	450	405	500
	3	680	430	430
3	2	620	550	500
	3	750	430	430
4	2	560	600	350
	3	540	550	520
5	2	370	480	810
	3	560	540	750
6	2	1000	1000	610
	3	450	720	420
7	2	240	310	510
	3	340	380	320
8	2	490	200	250
	3	420	440	360

Table VII shows the obtained ΔV scores (for translation) for each subject on the unfamiliar or test IC as a function of update rate. Again, there was no significant difference in ΔV as a function of update rate. A Rank Test for Matched Data indicated not rejecting the null hypotheses.

Figures 26 and 27 shows the obtained ΔV scores for each subject on each update rate for the test trials plotted with the calculated theoretical minimum ΔV versus time to rendezvous curves. The distribution of this plot is similar to that of the training trials.



Figures 26 - 27. Minimum and Obtained ΔV vs Time to Rendezvous - Test Trials.

Table VIII shows the obtained ΔV's as a function of update rate for each subject on each test trial. Again, there is no significant difference in $\Delta\theta$ as a function of update rate. A Rank Test for Matched Data indicates not rejecting the null hypothesis .

Control Strategy

Time histories of thrust inputs were recorded for each rendezvous maneuver. As in the first comparative study of off-line and on-line prediction, plots were made of thrust inputs as a function of elapsed time to rendezvous. Figure 28 shows such a data plot for IC 1. This plot is representative of the plots for IC 2, 3, and 4. It is clear from the figure that there is no difference in control strategy as a function of update rate.

Trajectory Plots

Figure 29 shows the trajectiories flown by a subject on the test trials (6 trials; 2 IC, 1 trial on each of the three update rates). These plots are typical of the performance of all subjects. It is clear from examination of the trajectory plots that no difference as a function of update rate exists.

TABLE VII

OBTAINED ΔV's AND TIME'S TO RENDEZVOUS FOR EACH SUBJECT ON EACH OF THE TEST TRIALS AS A FUNCTION OF UPDATE RATE.

		Update Rate					
		Continuous		25 seconds		50 seconds	
Subject	IC	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)	ΔV (ft/sec)	Time (Min)
1	1	125	39,1	92	38.4	75	44.4
	4	183	32.2	210	55.2	201	53.2
2	1	88	54.4	82	54.4	88	42.9
	4	173	48.2	172	51.4	125	31.4
3	1	75	49.2	72	41.3	60	42.1
	4	210	62.4	132	55.1	150	55.4
4	1	105	41.4	100	40.2	99	40.4
	4	158	50.4	160	41.4	165	52.4
5	1	85	52.4	75	42.4	80	45.2
	4	150	50.1	163	46.4	140	56.4
6	1	89	50.4	85	56.6	88	50.4
	4	145	54.8	140	57.4	158	53.4
7	1	68	46.1	75	42.4	75	40.6
	4	183	52.4	175	53.6	165	49.6
8	1	75	37.4	75	46.8	76	41.0
	4	150	54.4	130	52.4	147	50.6

TABLE VIII

OBTAINED Δ'S FOR EACH SUBJECT ON EACH OF THE TEST TRIALS AS A FUNCTION OF UPDATE RATE.

		Update Rate		
Subject	IC	Continuous Δθ(in degrees)	25 seconds Δθ(in degrees)	30 seconds Δθ (in degrees)
1	1	690	320	360
	4	620	820	580
2	1	240	240	310
	4	350	440	250
3	1	560	730	370
	4	1000	550	340
4	1	630	570	510
	4	500	300	640
5	1	600	450	1000
	4	850	940	630
6	1	550	700	520
	4	1000	1000	870
7	1	460	480	620
	4	440	790	500
8	1	480	500	550
	4	590	800	540

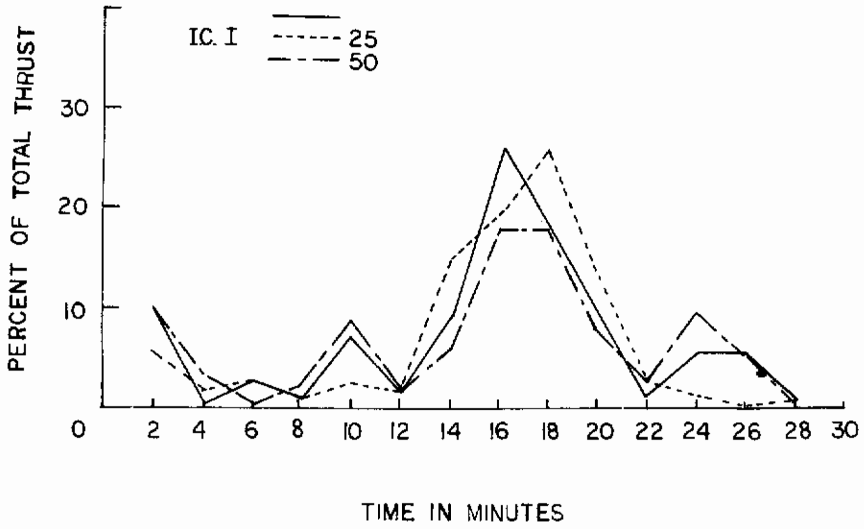


Figure 28. Percent of Total Thrust vs Time.

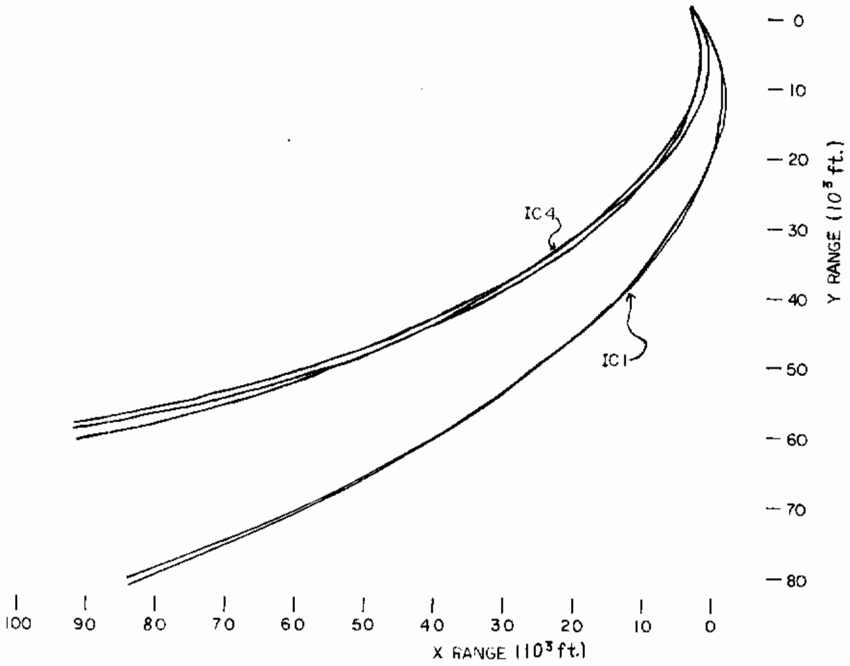


Figure 29. Trajectory Plots.

CONCLUSIONS

The results of the two experiments reported here may be summarized as follows:

1. Under the conditions studied, both on-line and off-line predictor techniques provided sufficient information to subjects to allow successful completion of rendezvous maneuvers.

2. Superior performance, in terms of reduced fuel consumption for translation and attitude control, was obtained when off-line prediction techniques were used.

3. The subject's control strategy more closely approached the two-impulse techniques when off-line predictor techniques were used.

4. Intermittent updating (25 and 50 second intervals between updates) of the predictor model did not effect subject's performance when off-line techniques were used.

5. The reduction of the scale factor (from 1 inch = 20,000 ft to 10 millimeters = 40,000 ft) on the predictor display for the intermittent update study did not produce levels of performance different from those obtained with the large display used in a prior study.

6. The additional information, regarding the relationship between time to rendezvous and fuel consumption for translation, presented to the subjects in the intermittant update study did not produce better performance. This is interpreted to mean that subjects could not make sufficiently accurate estimates of arrival time from the predictor display.

APPENDIX I

Circuit Diagrams

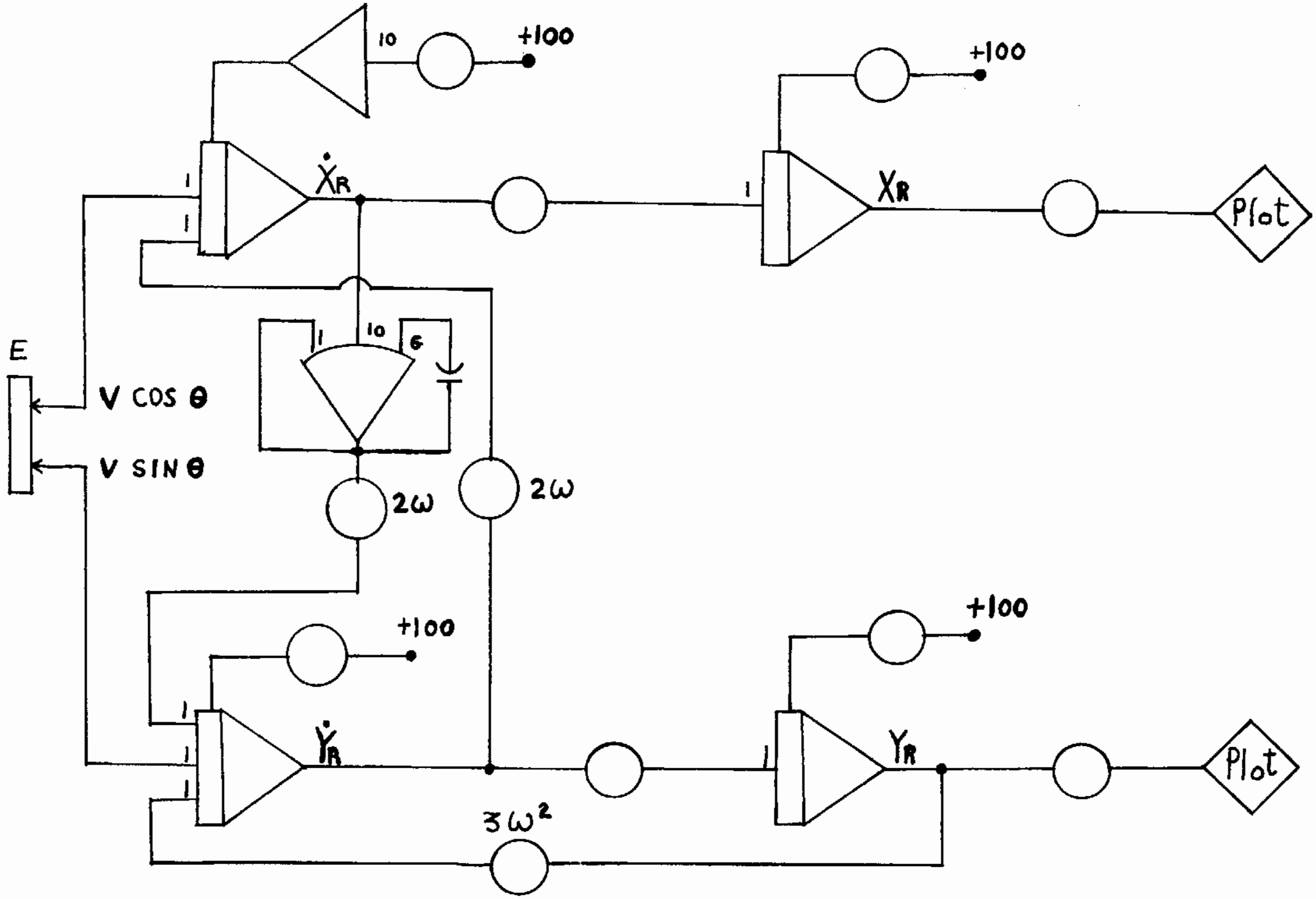
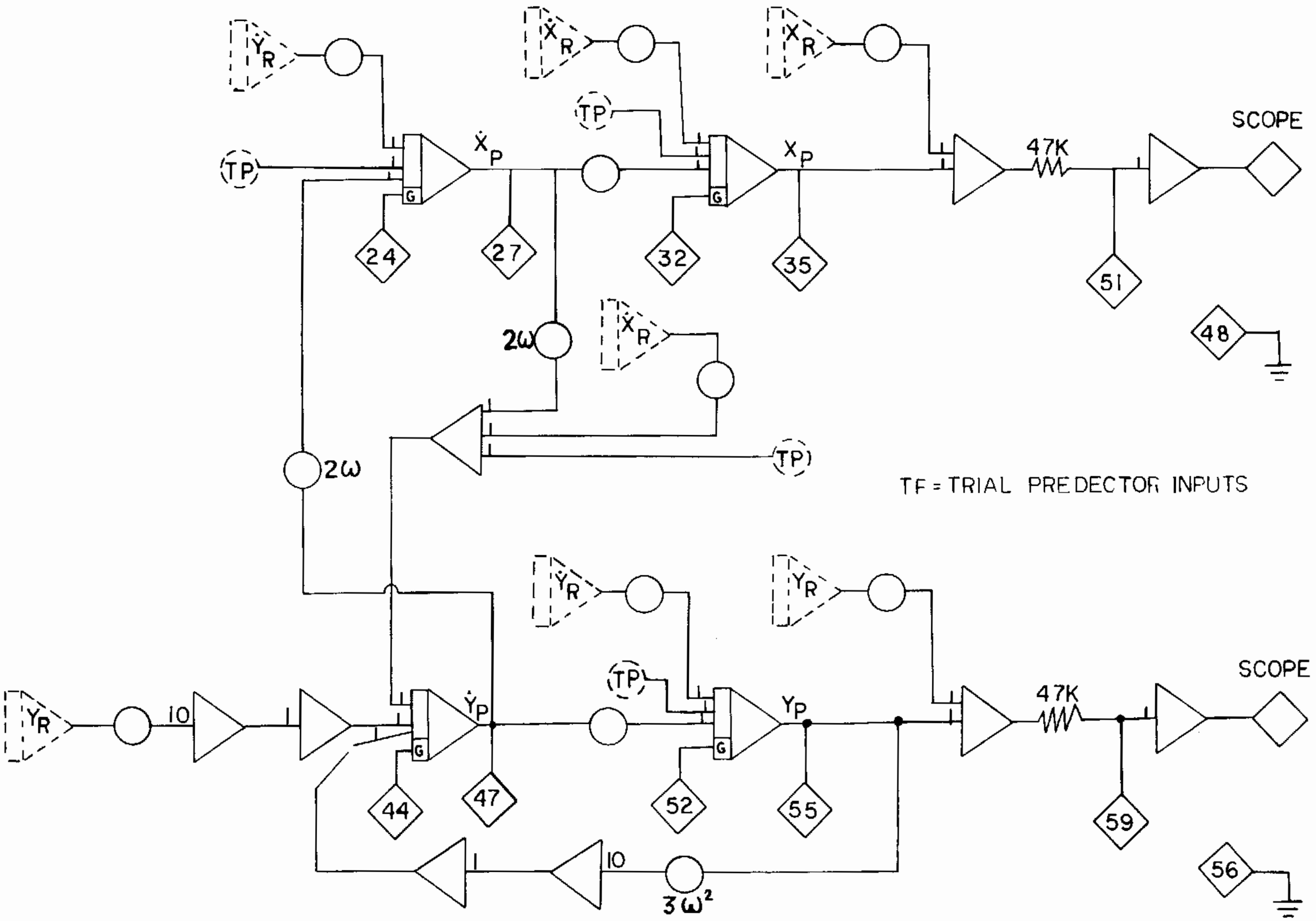


Figure 30. Ṙeal Time Circuit



TF = TRIAL PREDECTOR INPUTS

Figure 31. Fast Time Circuit

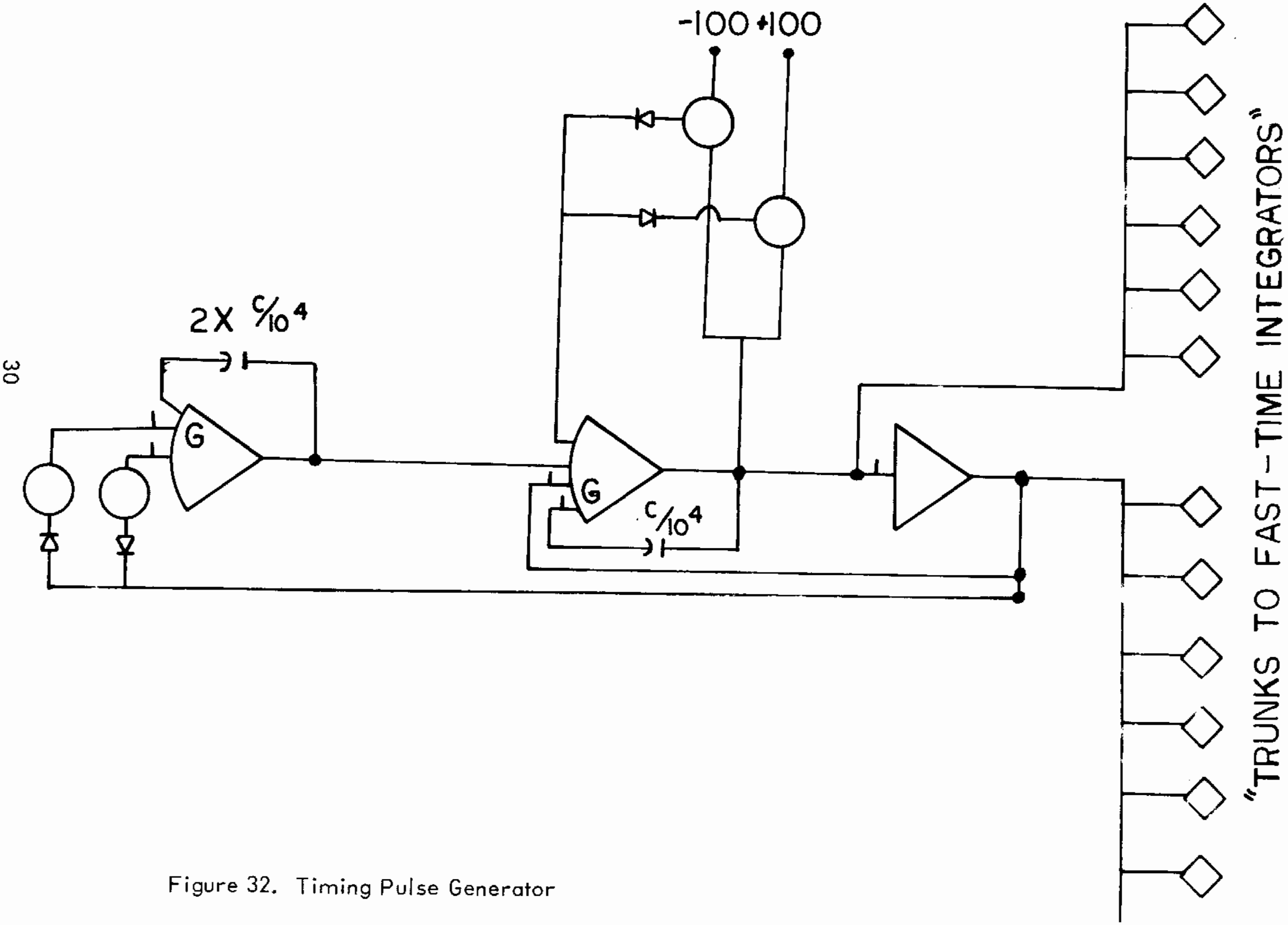


Figure 32. Timing Pulse Generator

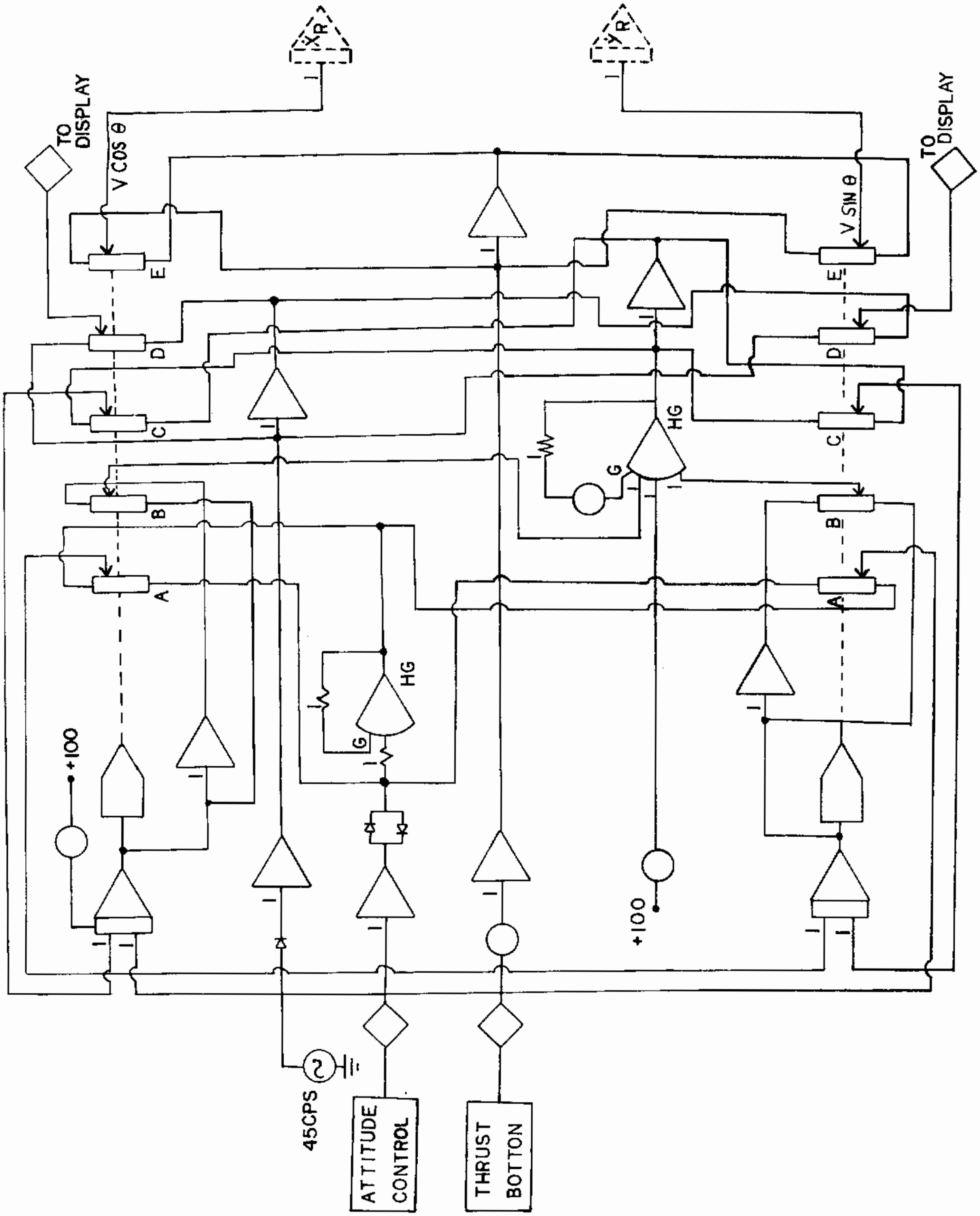


Figure 33. Pitch-Thrust System Circuit

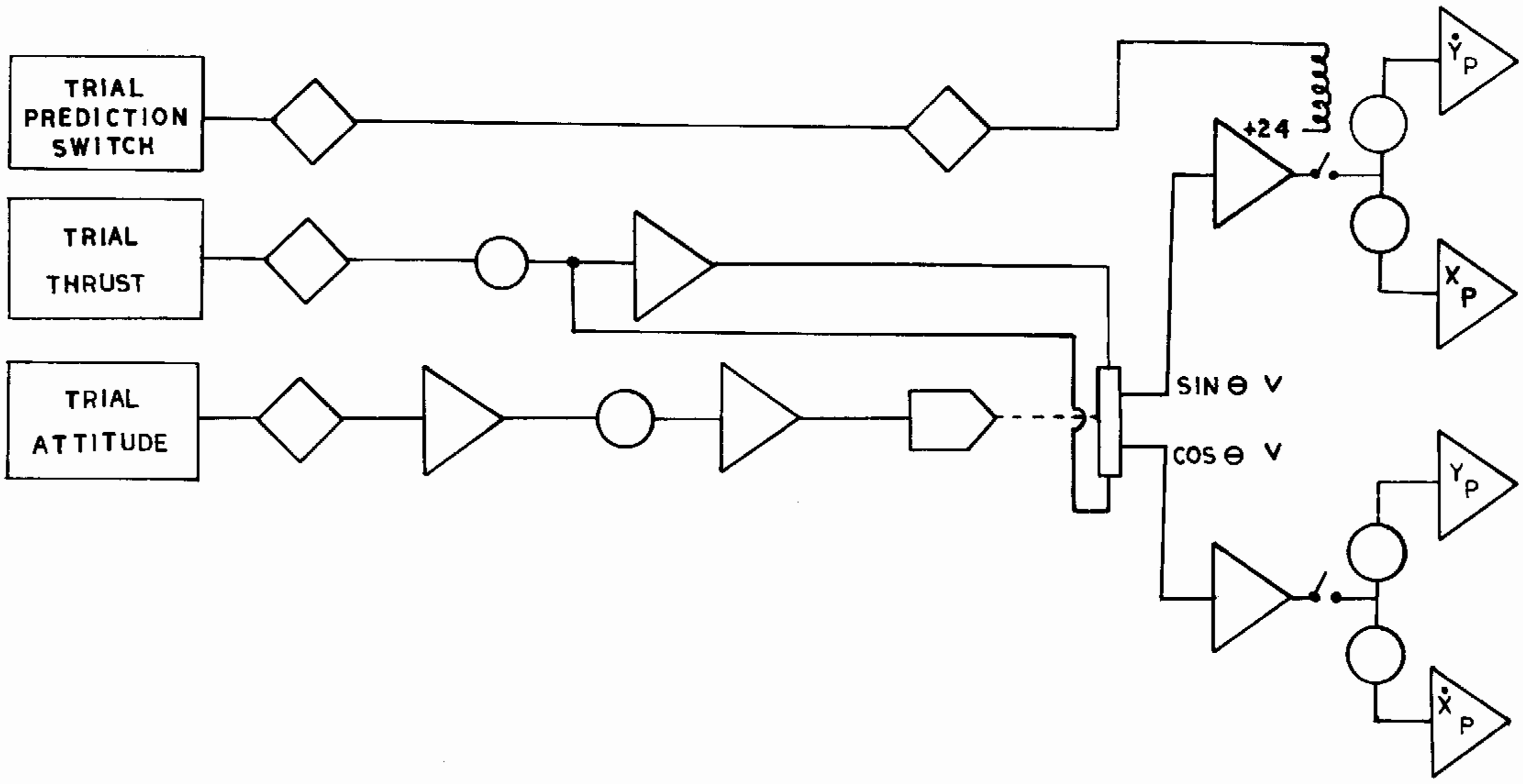


Figure 34. Trial Predictor Circuit

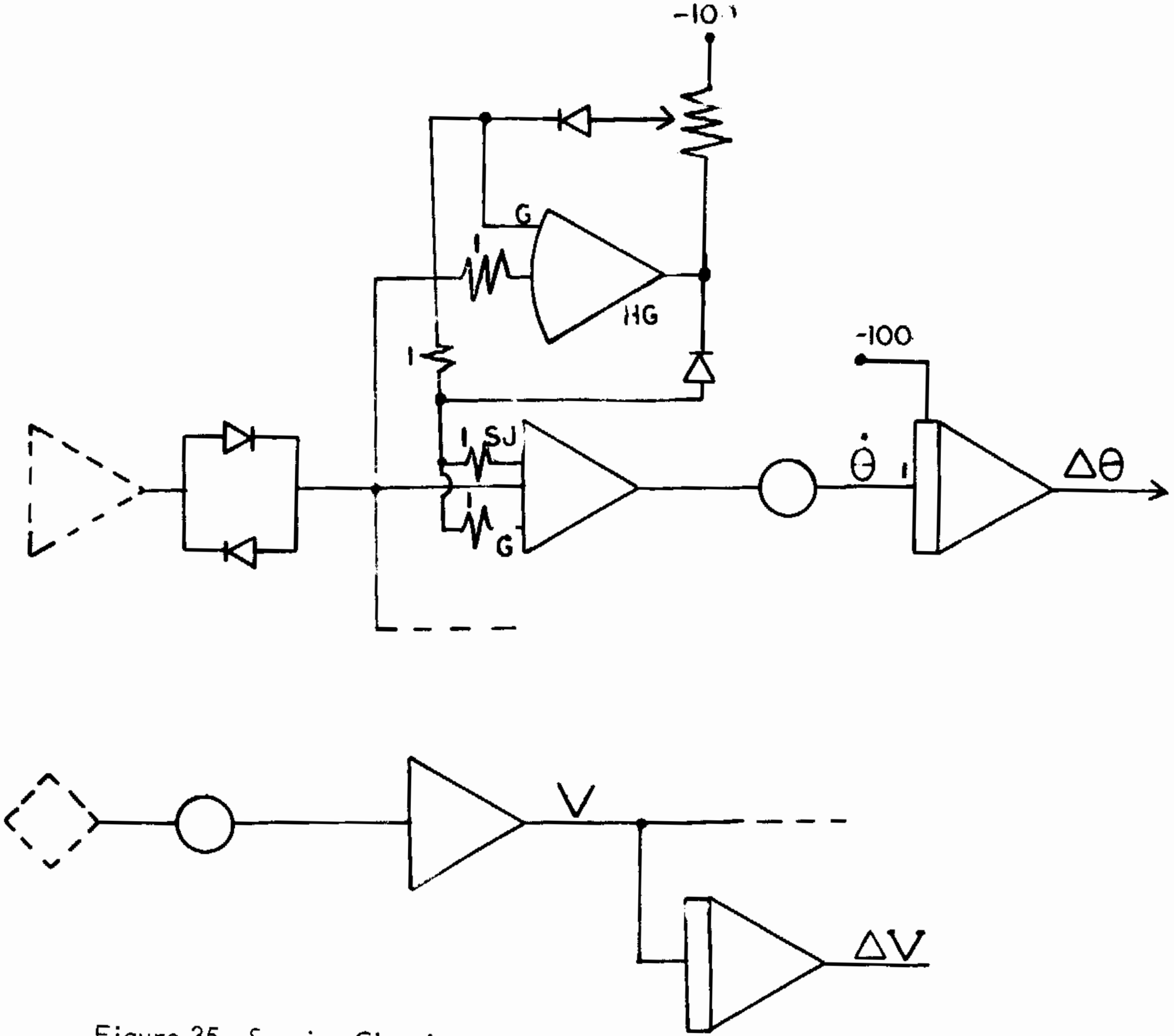


Figure 35. Scoring Circuit

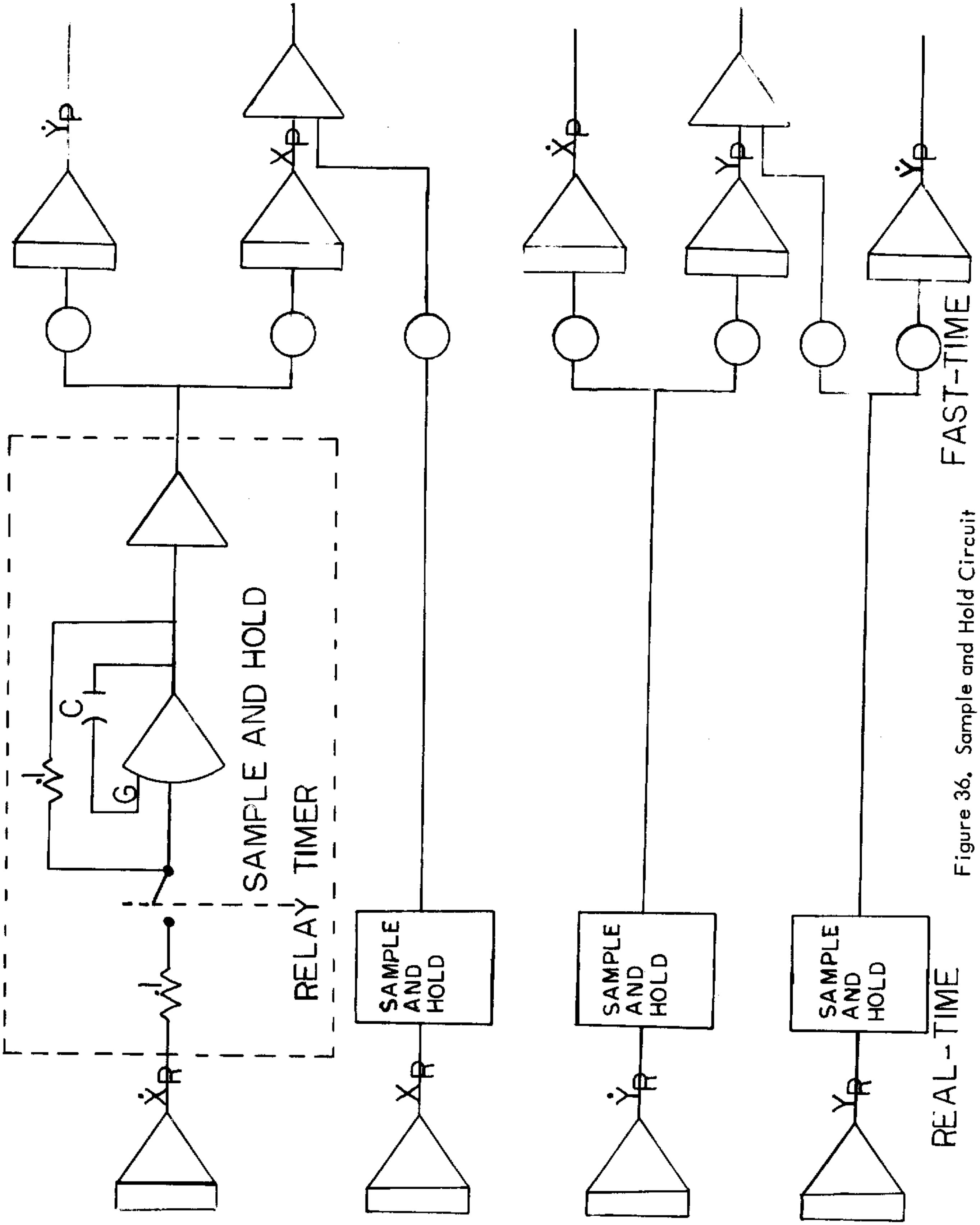


Figure 36. Sample and Hold Circuit

Appendix II

INSTRUCTIONS TO SUBJECTS

I. Purpose of Study

The purpose of the study is to investigate a display technique for performing orbital rendezvous maneuvers. You will be performing such maneuvers under several simulated conditions, and it is important that you understand your task thoroughly. Listen carefully to the following instructions and feel free to ask questions as necessary.

II. Orbital Dynamics

The following disucssion is to acquaint you with some orbital dynamics.

Look at figure 1.

The first figure shows a space vehicle in orbit around the earth. Orbit I 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 ellipsee, 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 as 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 behind and above and below the target vehicle.

Consider the path of a second vehicle attempting to rendezvous with the target vehicle. Look at figure 3c. If the second vehicle is initially behind and below the target it must speed up to catch it. Speeding up will also cause the interceptor to gain altitude so care must be taken to control this altitude gain to avoid paths 1 and 3. If the proper combination of thrusts are applied path 2 could be followed. All that would remain then would be to decelerate so that at intercept the relative velocity would be zero.

III. Relative Motion Display

Look at figures 4 and 5.

You may have noticed that the relative motion shown in figure 3c was not like the actual motion shown in figures 1 and 2. Figures 4 and 5 explain why this difference exists.

The target is in a circular orbit as shown in figure 4. The interceptor's orbit is an ellipse also shown in figure 4.

If the position of the interceptor is determined in a rotating coordinate system centered on the target, as the target proceeds along its orbit, the resulting display is like that shown in figure 5. This is a display of relative motion where the target appears fixed and the interceptor moves.

IV. Task Description

Now I will describe your task in detail. Look at the display here (point). The dot on the right hand side of the display represents the target vehicle. The dot on the left hand side represents the interceptor which you will control. As you can see your starting position on this run is below and behind the target.

(Start problem)

Notice the trace on the display. Again the left hand end of the trace shows your present position relative to the target. The trace shows your predicted path for a 25 minute period. That is, if no control action is taken the trace shows the path you will follow relative to the target.

To control the interceptor's path you will use these controls (point to control stick and attitude indicator). The stick on the left controls the attitude of the interceptor. This display shows you your pitch attitude. The button on the stick on your right fires the thruster on the interceptor. To change the path of the interceptor you pitch your vehicle to the desired attitude and fire our thruster (demonstrate).

Your task will be to rendezvous with the target within the time to use as little fuel or thrust as possible. That is, fly the interceptor to the target and stop using as little thrust as possible. This clock (point) will indicate the time elapsed from the start of the run.

We want you to get the interceptor within 1000 ft which means your interceptor should be right on the target and reduce your velocity to 10 ft/sec, which means the trace should be 1/8" long.

You can see that as you slow the interceptor down the trace reduces in length. Since the trace always represents 25 minutes of predicted path its length, this is a good cue for relative velocity.

You will be starting the rendezvous maneuver under several different conditions. Also you will have two display conditions. One condition is just as you have seen here with the predicted path. The other condition will be the same but with an addition; a trial predictor.

This (point) trial predictor will allow you to try out pitch attitude and thrust without actually thrusting the interceptor.

(Start problem)

The knob labeled Trial Attitude is for trying out pitch attitudes. Notice that it can be set + or - 165 from the zero pitch condition. The knob labeled trial thrust is for trying various thrust levels. It can be set from 0 to 100 ft/sec. The toggle switch activates the trial system. (Demonstrate)

You will have 16 rendezvous maneuvers to perform. We will tell how you did after each maneuver. Remember, we want you to use as little fuel as possible yet complete the rendezvous in 30 minutes.

Are there any questions?

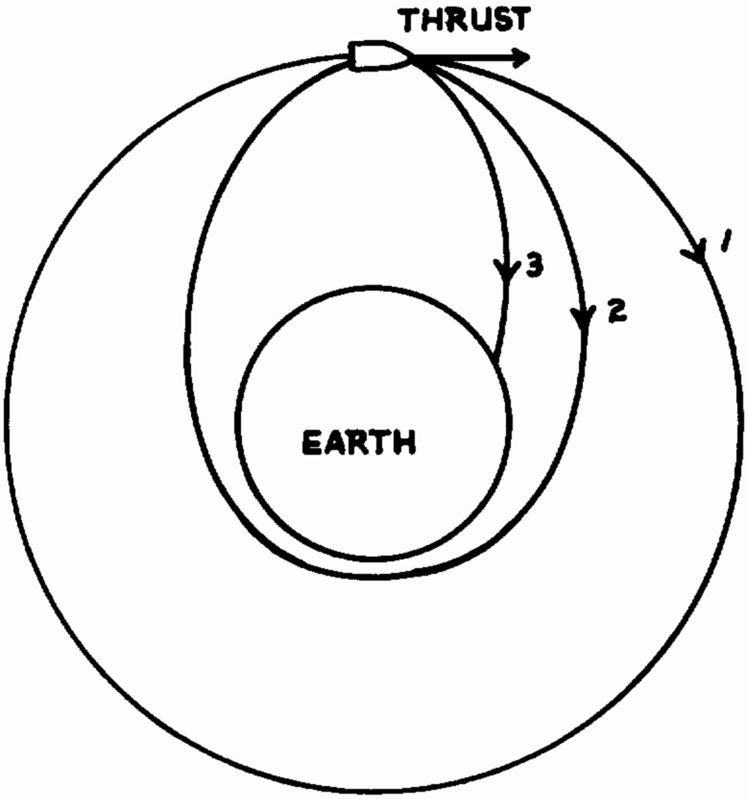


Figure 1

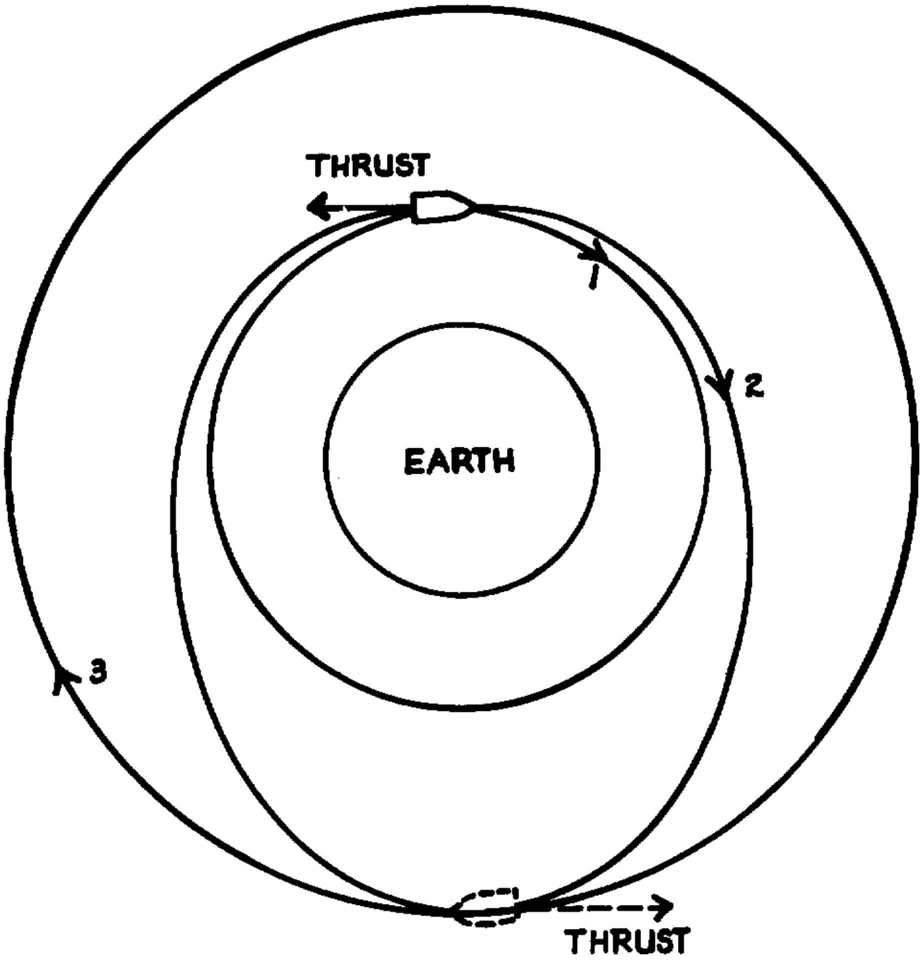


Figure 2

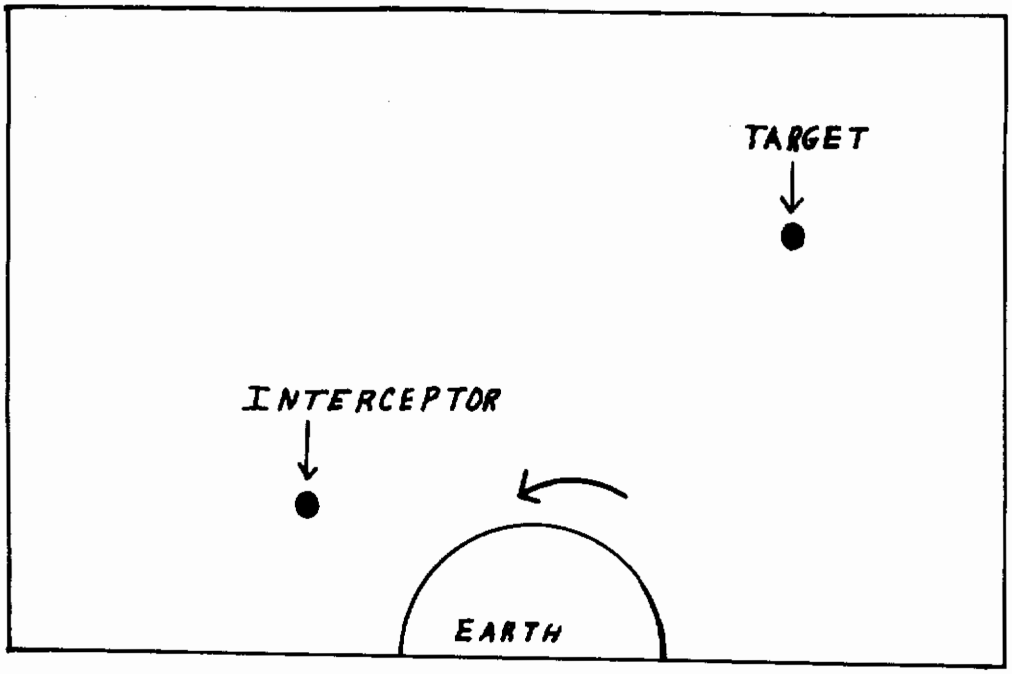


Figure 3a

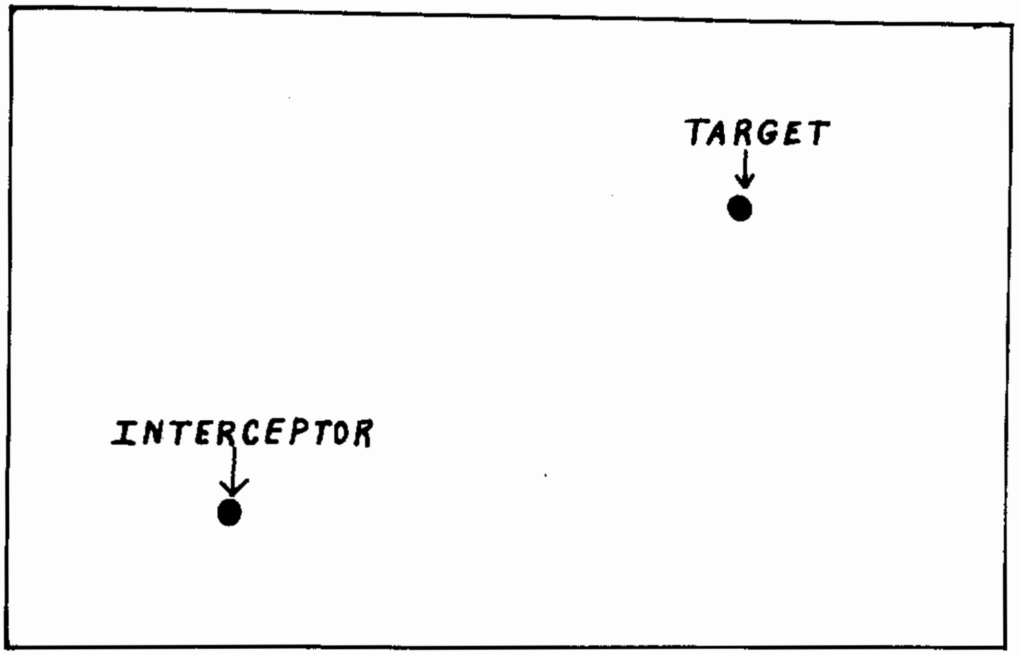


Figure 3b

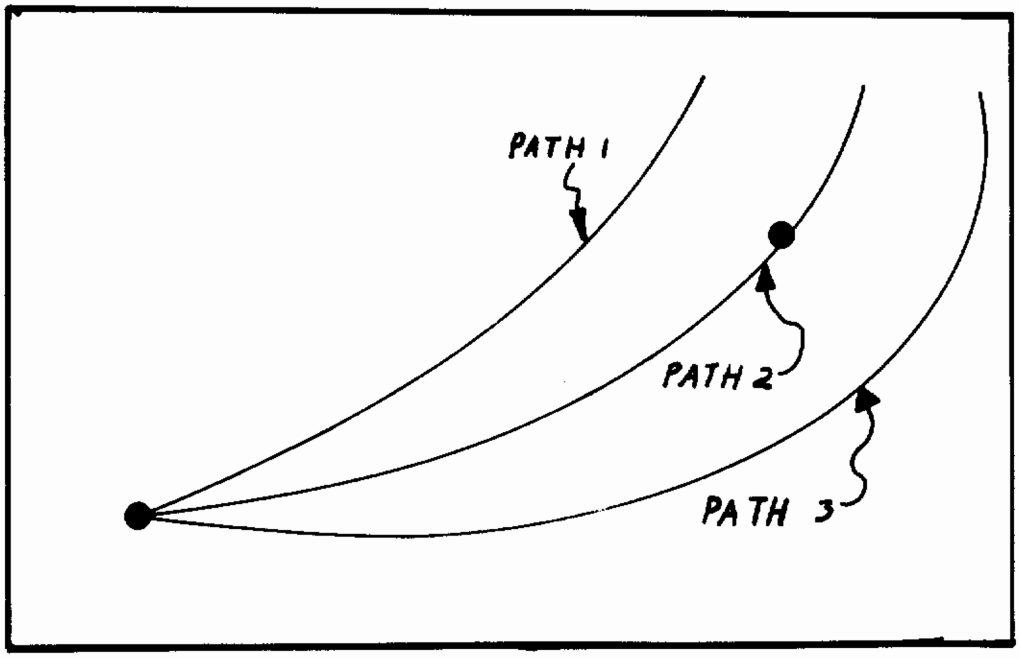


Figure 3c

Appendix III

Calculation of Minimum ΔV

Terms

$\dot{x}$ = initial x velocity to achieve a two-impulse transfer in time (t)

$\dot{y}$ = initial y velocity to achieve a two-impulse transfer in time (t)

$\dot{x}_o$ = initial X velocity at the start of a rendezvous maneuver

$\dot{y}_o$ = initial y velocity at the start of a rendezvous maneuver

x_o = initial range from the target in the x axis

y_o = initial range from the target in the y axis

t = time to rendezvous

d = time of sight range to the target

ω = angular velocity of rotation of the coordinate system relative to inertial space

ΔV = total velocity increment to complete a rendezvous

Calculations

The minimum ΔV for a two-impulse transfer, assuming no wait time, or "fire now" is given by the following expression:

$$\text{Minimum } \Delta V_{\text{total}} = \Delta V_1 + \Delta V_2$$

where

ΔV_1 (the velocity increment to achieve a collision course)

$$= \overline{\dot{x} + \dot{y}} - \overline{\dot{x}_o + \dot{y}_o}$$

where

$$\dot{x} = \frac{\omega \quad -x_o + y_o \left(6 \quad \omega t + \cot \omega t - \frac{1}{\sin \omega t} - 8 \tan \frac{\omega t}{2}\right)}{8 \tan \frac{\omega t}{2} - 3\, \omega t}$$

and

$$\dot{y} = \frac{y_o\, \omega (-4 + 3 \cos \omega t)}{\mathrm{Sin}\ \omega t} - 2 \tan \frac{\omega t}{2}\, \dot{x}$$

and

ΔV_2 (the velocity increment to match velocities with the target)

$$= \sqrt{3\, \omega^2 (y_o)^2 + (\overline{\dot{x} + \dot{y}})^2}$$

To obtain the ΔV vs time to rendezvous curves for each IC, ΔV's were calculated for the following rendezvous times

t_1 = 1800 seconds

t_2 = 2400 seconds

t_3 = 3000 seconds

t_4 = 3600 seconds

t_5 = 4200 seconds

REFERENCES

1. McCoy, W. K., Jr., and G. G. Frost, Time History as an Information Source for Operator Control of Orbital Rendezvous, AMRL-TDR-64-55 (AD 603 597), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, June 1964.

2. McCoy, W. K., Jr., and G. G. Frost, Investigation of "Predictor" Displays for Orbital Rendezvous, Program Summary, AMRL-TR-65-138 (AD 624 467), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, September 1965.

3. Clark, Herbert J., Trajectory Versus Line of Sight Space Rendezvous Using Out-of-Window Visual Cues, AMRL-TR-65-10 (AD 615 157), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, February 1965.

4. Kasten, D. P., Human Performance in a Simulated Short Orbital Transfer, AMRL-TDR-62-138 (AD 400 484), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, December 1962.

5. Mueller, D. D., Relative Motion in the Docking Phase of Orbital Rendezvous, AMRL-TDR-62-124 (AD 402 384), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, December 1962.

6. Bradley, J. V., Distribution-Free Statistical Tests, WADD-TR-60-661 (AD 249 268), Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, August 1960.

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)*

Ritchie Inc.
44 S. Ludlow
Dayton, Ohio 45402
&
Aerospace Medical Research
Laboratories*, Wright-
Patterson AFB, Ohio 45433

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP
N/A

3. REPORT TITLE

PREDICTOR DISPLAY TECHNIQUES FOR ON-BOARD TRAJECTORY OPTIMIZATION OF RENDEZVOUS MANEUVERS

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

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

McCoy, William K., Jr.
*Frost, George G.

6. REPORT DATE April 1966	**7a. TOTAL NO. OF PAGES** 44	**7b. NO. OF REFS** 6

8a. CONTRACT OR GRANT NO. Prepared in part
AF 33(615)-2353

b. PROJECT NO. 7184

c. Task No. 718402

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
AMRL-TR-66-60

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

Predictor displays for orbital rendezvous present to the pilot target position, interceptor position, and a continuous prediction of the interceptor trajectory relative to the target. Two experiments using rendezvous predictor displays are reported: (1) a comparison of on-line and off-line predictor techniques, and (2) a comparison of intermittent versus continuous updating of the prediction. All conditions tested yielded successful rendezvous performance. Off-line prediction, where the pilot could, at will, interrogate the predictor without expending fuel, was demonstrated to be significantly better than on-line prediction where the pilot could see only his actual predicted path. Intermittent updating produced no significant degradation of performance with update rates as low as once per 50 seconds.

DD FORM 1 JAN 64 1473

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Off-line Prediction						
Rendezvous						
Intermittent updating						
Simulation						

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