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DOCKING SIMULATION ANALYSIS OF RANGE DATA REQUIREMENTS FOR THE ORBITAL MANEUVERING VEHICLE

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Science and Engineering Directorate

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16. ABSTRACT

This report describes the approach and results of an initial study to assess the controllability of the Orbital Maneuvering Vehicle (OMV) for terminal closure and docking. The vehicle characteristics used in this study are those of the Marshall Space Flight Center (MSFC) baseline OMV which were published with the Request for Proposals for preliminary design of this vehicle. This simulation was conducted at MSFC using the Target Motion Simulator. The study focused on the OMV manual mode capability to accommodate both stabilized and tumbling target engagements with varying complements of range and range rate data displayed to the OMV operator. Four trained test subjects performed over 400 simulated orbital dockings during this study. A firm requirement for radar during the terminal closure and dock phase of the OMV mission was not established by these simulations. Fifteen pound thrusters recommended in the MSFC baseline design were found to be advantageous for initial rate matching maneuvers with unstabilized targets; however, lower thrust levels were desirable for making the final docking maneuvers.

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TABLE OF CONTENTS

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LIST OF ILLUSTRATIONS

TECHNICAL MEMORANDUM

DOCKING SIMULATION ANALYSIS OF RANGE DATA REQUIREMENTS FOR THE ORBITAL MANEUVERING VEHICLE

INTRODUCTION

This report describes the approach and results of an initial simulation study to assess the controllability of the Orbital Maneuvering Vehicle (OMV) for terminal closure and docking. The vehicle characteristics used in this study are those of the Marshall Space Flight Center (MSFC) baseline OMV which were published with the Request for Proposals for preliminary design of this vehicle. The concept for remote manual control of the OMV is shown in Figure 1. This simulation study was conducted at MSFC using the Target Motion Simulator (TMS). This initial study has focused on the OMV manual mode capability to accommodate both stabilized and tumbling target engagements with varying complements of range and range rate data displayed to the pilot.

OBJECTIVES

The primary objective of this study as well as the succeeding studies planned this year for the TMS is to evaluate the MSFC baseline configuration, in general, and the point design man-in-the-loop control system in particular. The long term objective is to evolve a manual control system design with the flexibility to accommodate those requirements which have been identified as significant design and/or cost drivers for the OMV. The two items chosen to be parameterized for this first study are radar sensor complement and target vehicle tumbling rates.

APPROACH

A. Vehicle Models

The following two vehicle models were implemented on the TMS.

1) Target Vehicle – The target vehicle selected for the study was the LANDSAT D. It is a 3800 lb satellite that is approximately 14 ft long and 7 ft in diameter. The RMS grapple fixture is mounted on the side of the vehicle and roughly opposite the vehicle center of gravity. The standard Remote Manipulator System (RMS) sighting aide T Bar was assumed for the study. A 12/1 scale model of LANDSAT (excluding appendages) was constructed and incorporated into the TMS.

2) Chase Vehicle – The OMV model used in the simulation is the MSFC Generic Baseline [1]. Fully loaded, this vehicle weighs 10,500 lb, is 138 in. in diameter, and 37 in. long. The RCS is configured with 15 lb thrusters arranged in eight orthogonal triads. The docking interface is assumed to be a RMS or RMS derivative end effector.

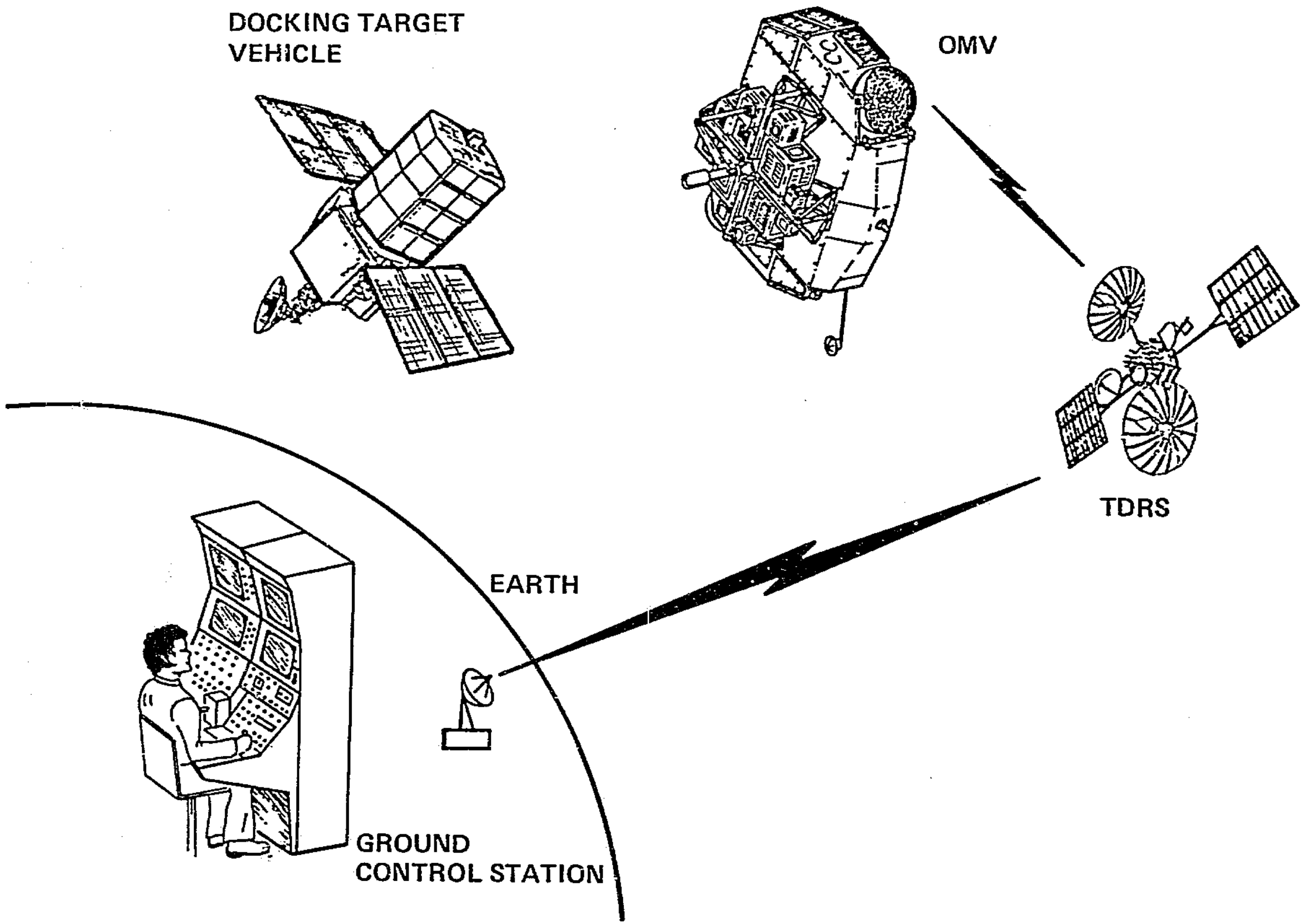


Figure 1. Remote control of the Orbital Maneuvering Vehicle.

B. Simulation

The Target Motion Simulator (TMS) was selected for the study. A software specification was prepared for the TMS [2] specifying the following:

1) Coordinate system definition

2) Translational equations of motion

3) Rotational equations of motion

4) Point design man-in-the-loop control system.

This software spec was integrated into the TMS and validated on the new VAX 11/750 computer.

C. Pilot Training

A corps of seven pilots was selected and trained on the TMS over a period of about three weeks. Pilot performance and "learning curve" data were documented in Reference 4. Four of these pilots were selected for this first study.

D. New Models

Three additional models were devised and incorporated into the TMS.

1) Initial condition generator

2) Radar model

3) Data base management system.

The initial condition generator [3] randomly selects the chase-to-target-vehicle line-of-sight angles, initial range, and initial translational rates. This prevents the pilot from becoming accustomed to a predictably finite set of start conditions and improves simulation fidelity. The radar model simply represents a uniform distribution around computed nominal values for range and range rates. The range error limits are set at ±0.5 ft and the range rate limits are set at ±0.1 ft/sec. The data base management system collects and stores selected end conditions at the conclusion of each simulation run. The capability to plot these end conditions versus a predetermined experiment test-plan independent variable such as target vehicle tumbling rates is also provided.

E. Communication Time Delay

Communication time delay will be the subject of a future simulation study. For this study, a constant time delay of 1.8 sec was assumed.

F. Criteria of Merit

The following end conditions were selected as indices of performance:

1) Docking end conditions — defined in the succeeding section on results.

2) Maximum closing velocity — none set.

3) RMS docking envelope.

a) ±10 deg roll

b) ±15 deg pitch and yaw

c) ±4 in. radial.

In addition to these end conditions, pilot debriefings were conducted during the course of the study followed by a comprehensive debriefing at study conclusion. Cooper-Harper Ratings were also obtained to quantify pilot opinion of the handling qualities of the simulated OMV.

G. Experiment Plan

Three separate combinations of range and range rate information to be displayed to the pilot were chosen for the study:

1) Range and range rate displayed

2) Only range rate displayed.

3) No radar information displayed.

Each radar configuration was evaluated for both stabilized and tumbling target engagements. Each pilot was advanced through the experiment plan run matrix (Fig. 2) by columns. For example, cases with radar Complement 1 (range and range rate) were run first beginning with a stabilized target and finishing with target vehicle rates on all axes. Cases with radar Complement 2 (range rate only) were run next, followed by the final set of runs with radar Complement 3 with no range or range rate displayed to the pilot. The target vehicle tumbling rates were, in general, varied according to the steps specified in Figure 2, however; adjustments were made to these steps as a function of pilot ability. The simulation was conducted over a period of approximately four weeks according to the schedule in Figure 3. The schedule was divided into 1-hr increments and each pilot flew no more than two sessions per day. Each pilot made one pass through the run matrix accounting for a total (four passes) of 360 simulation runs.

DESCRIPTION OF SIMULATION FACILITY

The implementation of the OMV simulation was accomplished using an MSFC orbital docking simulation facility consisting of a remote control station, a simulation computer, and a TMS. This implementation is depicted on Figure 4. The simulation computer was a VAX-11/750. The remote control station was a generic control console soon to be replaced with one which more closely resembles a ground control station for OMV. The TMS was built inhouse at MSFC over 15 years ago and provided the real time video images for representation of the OMV TV camera view as it approached a target vehicle.

RADAR COMPLEMENT →	1 (R & $\dot{R}$)	2 ($\dot{R}$)	3 (NO RADAR)
STABILIZED TARGET			
ROLL RATE ONLY .1 – 2.0 d/sec. d/SEC. STEPS OF .2			
PITCH RATE ONLY .1 – 2.0 d/SEC. STEPS OF .2			
ROLL, PITCH & YAW RATES .1 – 1.0 d/SEC. STEPS OF .1			

ASSUMPTIONS:

- TARGET MODEL – LANDSAT
- OMV MODEL – MSFC
- ROTATION STICK – RP
- TRANSLATIONAL – ACCEL
- COMMUNICATION TIME DELAY – 1.8 SEC

RUN PROCEDURE:

- ADVANCE RUN MATRIX BY COLUMNS (INCREMENT ROWS FIRST)
- COMPLETE RUN MATRIX FOR EACH OF 4 PILOTS
- TOTAL NUMBER OF RUNS PER PILOT ≈ 100
- PLOT TARGET RATES ON ABCISSA

Figure 2. Experiment run matrix.

DATES	JANUARY 14, 21, 28	JANUARY 15, 22, 29	JANUARY 16, 23, 30	JANUARY 17, 24, 31	JANUARY 18, 25, FEBRUARY 1
TIME \ DAY	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
8 – 9		SHARKEY	REISZ	SLONE	SHARKEY
9 – 10	SLONE	DABNEY	SHARKEY	REISZ	SLONE
10 – 11	REISZ	SLONE	DABNEY	SHARKEY	REISZ
11 – 12	B R E A K				
12 – 1	SHARKEY	REISZ	SLONE	DABNEY	SHARKEY
1 – 2	DABNEY	SHARKEY	REISZ	SLONE	DABNEY
2 – 3	SLONE	DABNEY	SHARKEY	REISZ	MAKE UP
3 – 4	REISZ	SLONE	DABNEY	DABNEY	

Figure 3. OMV docking simulation schedule.

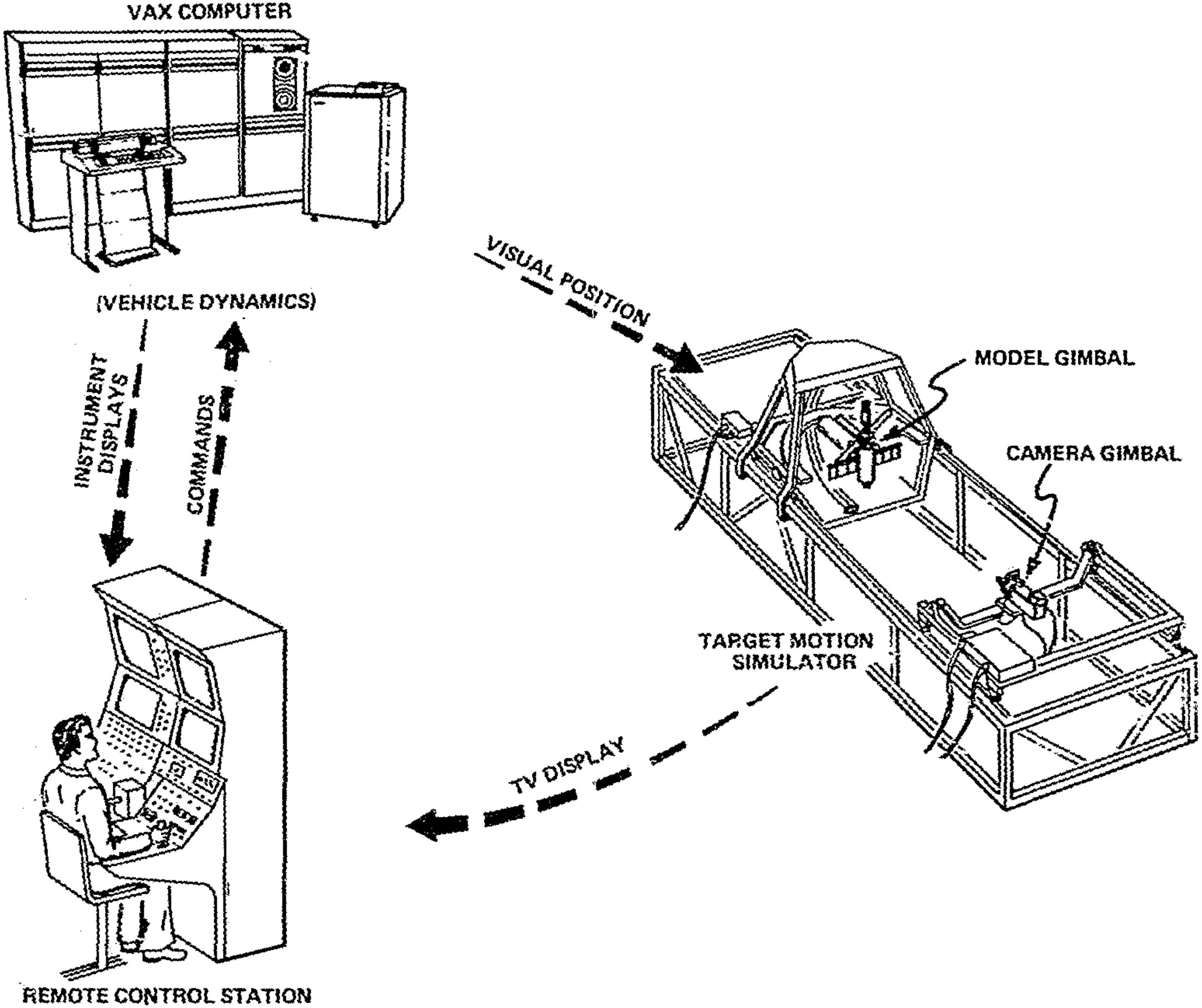


Figure 4. MSFC orbital docking using TMS.

A. Remote Control Station

The control station utilized in this simulation, although not equipped with state-of-the-art displays, provided the required information to the OMV test subjects. A photograph of this control station is shown in Figure 5. A 14-inch TV monitor provided a black and white video display having a standard 525 scan line format. Dedicated digital displays were located directly beneath the TV monitor and provided radar range and radar range rate data to the operator. As called for by the simulation objectives, the radar information was not provided in some cases and in others only radar range rate data was displayed.

The hand controls used were generic laboratory type control sticks having motions typical of those used for manual control of an orbiting vehicle. Attitude rate commands were provided by the right hand control stick which had roll, pitch, and yaw movements. Translation acceleration commands were provided in three axes by the left hand control stick. The attitude control stick had outputs which were proportional to the square of stick deflection. It had a spring return-to-neutral operation.

A special mode of operation was provided by the vehicle attitude rate control system in order to assist the test subjects in docking with rotating targets. The operator could establish an OMV rotation and automatically hold this rotation rate by engaging the trigger switch on the attitude control stick. Subsequent stick deflections were then used for perturbations about this established rotation rate. This mode of operation could be used as a vernier control in order to alleviate some of the difficulty of docking to a rotating target. Attitude rate hold was provided in all three axes.

Translation commands to the OMV were provided by the left hand control stick. It operated as a discrete "ON-OFF" acceleration command to the vehicle in the ±X, ±Y, and ±Z direction. This control stick also had a spring return-to-neutral action as well as a detent feel whenever a command was initiated.

The seat used in the remote control station was a commercial airline pilot's seat identical to that used in the Boeing 737 transport aircraft. It had adjustments in the fore and aft direction by means of rails attached to the floor. Seat height, tilt of the seat back, and position of arm rests were also adjustable. This seat was installed at the remote control station upon recommendation of MSFC human factors specialists. This recommendation resulted through experience gained from the test subject training exercises in which an upholstered computer console chair with casters was used. Test subjects found that the computer console chair became uncomfortable and caused fatigue during the long periods of sitting required for the orbital docking training exercises.

B. Simulation Computer

The computer used for operating this OMV docking simulation was a Digital Equipment Corp. (DEC) VAX-11/750. A block diagram of this computer system and its interfaces to docking simulator hardware is shown in Figure 6. It was configured to have four megabytes of memory, a floating point accelerator to increase throughput and improve execution time, and direct memory access controllers for high speed input/output operations. Thirty-two channels of both analog-to-digital and digital-to-analog converters were provided for interfacing the VAX computer with the ground control station and the TMS. Peripheral equipment provided for the VAX included a DEC model RA-80 Winchester Disk having 121 megabytes of memory, two Kennedy model 9300 tape units, a line printer, four CRT terminals, and two hard copy units.

Figure 5. Simulated remote control station.

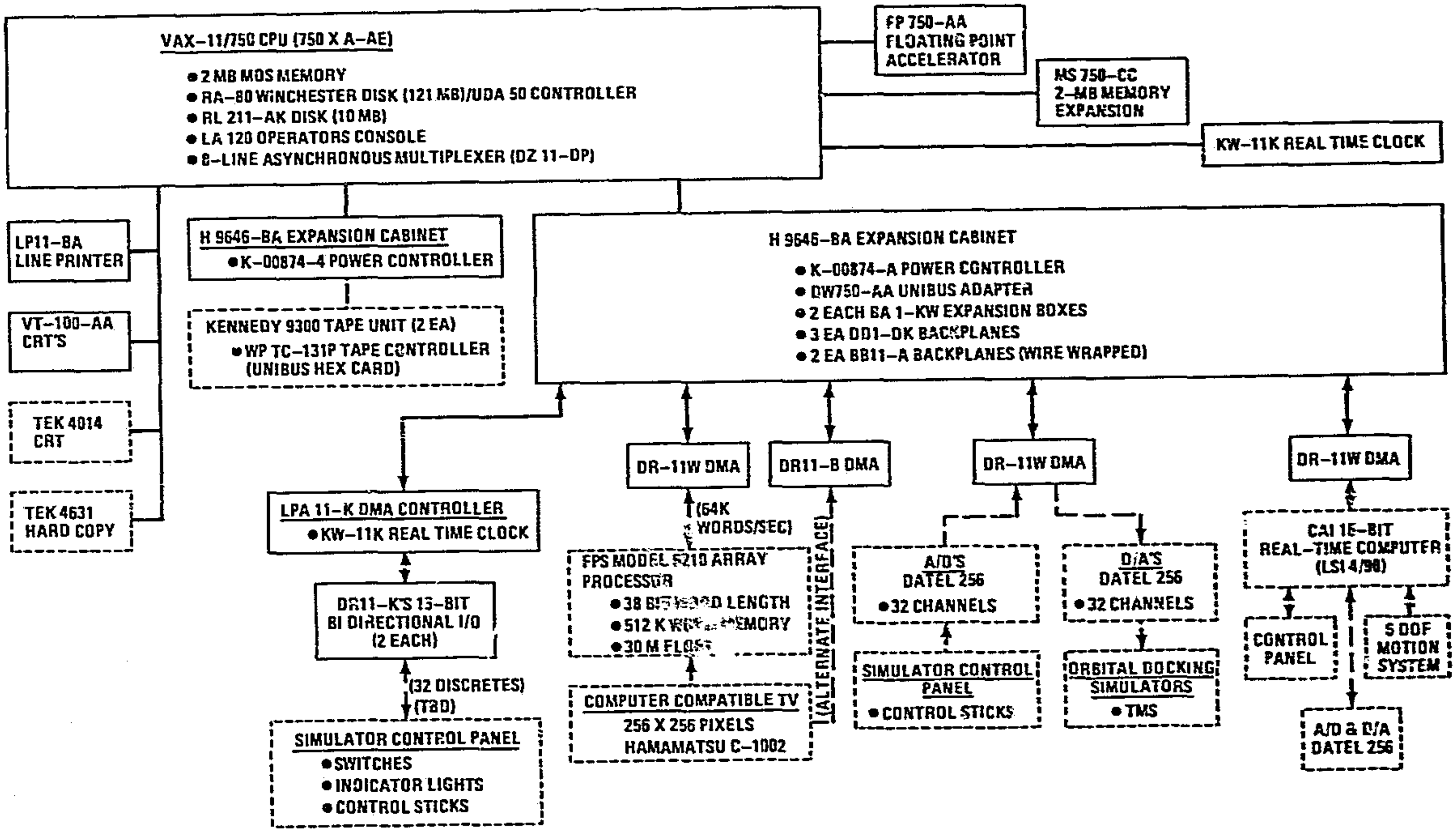


Figure 6. OMV simulation computer system.

The computer program used for this study was an adaptation of orbital docking simulations developed and used at MSFC for a number of years. A block diagram of the computer program and its interfaces to docking simulation devices is provided in Figure 7. This program was implemented for the first time on the VAX system for this simulation study. It had a solution time of 0.0285 sec. The program consisted of approximately 3,800 lines of code and included routines for the following real-time simulations:

1) OMV Reaction Control System (RCS) was modeled and consisted of 24 thrusters with typical moment arms and selectable force output levels. For this particular study the RCS thruster size was selected to be 15 lb.

2) Thruster firing logic was represented for maneuvering the OMV in six degrees-of-freedom. Simultaneous attitude and translation commands were possible. Translational motion was implemented as an "ON-OFF" acceleration command from the left hand control stick. Rotational motion of the OMV was a rate command proportional to the square of the deflection of the right hand control stick.

3) Mass property data based on the OMV reference design was represented.

4) The target vehicle rotational motion was maintained in a local vertical hold for some test conditions. An unstabilized target was also represented for three different motions: roll only, pitch only, and concurrent roll, pitch, and yaw rotations. For the cases of single axis motion in roll or pitch, the rotational rates varied to a maximum of 2 deg/sec in increments of 0.2 deg/sec. Worse cases were provided in which the target rotated simultaneously about all three body axes at 0.1 deg/sec increments up to a maximum of 1 deg/sec.

5) Orbital mechanics were included and were detectable as a secondary effect in influencing orbital docking performance.

6) Position commands to the TMS were calculated to provide video images of the relative location and orientation of the target vehicle with respect to the OMV. These commands enabled visual six degrees-of-freedom and consisted of the following:

a) Target gimbal yaw

b) Target gimbal pitch

c) Target gimbal translation

d) Camera gimbal roll

e) Camera gimbal yaw

f) Camera gimbal pitch

g) Focus servo for camera image tube position.

7) Display commands were generated for the digital readouts on the remote control station. These consisted of:

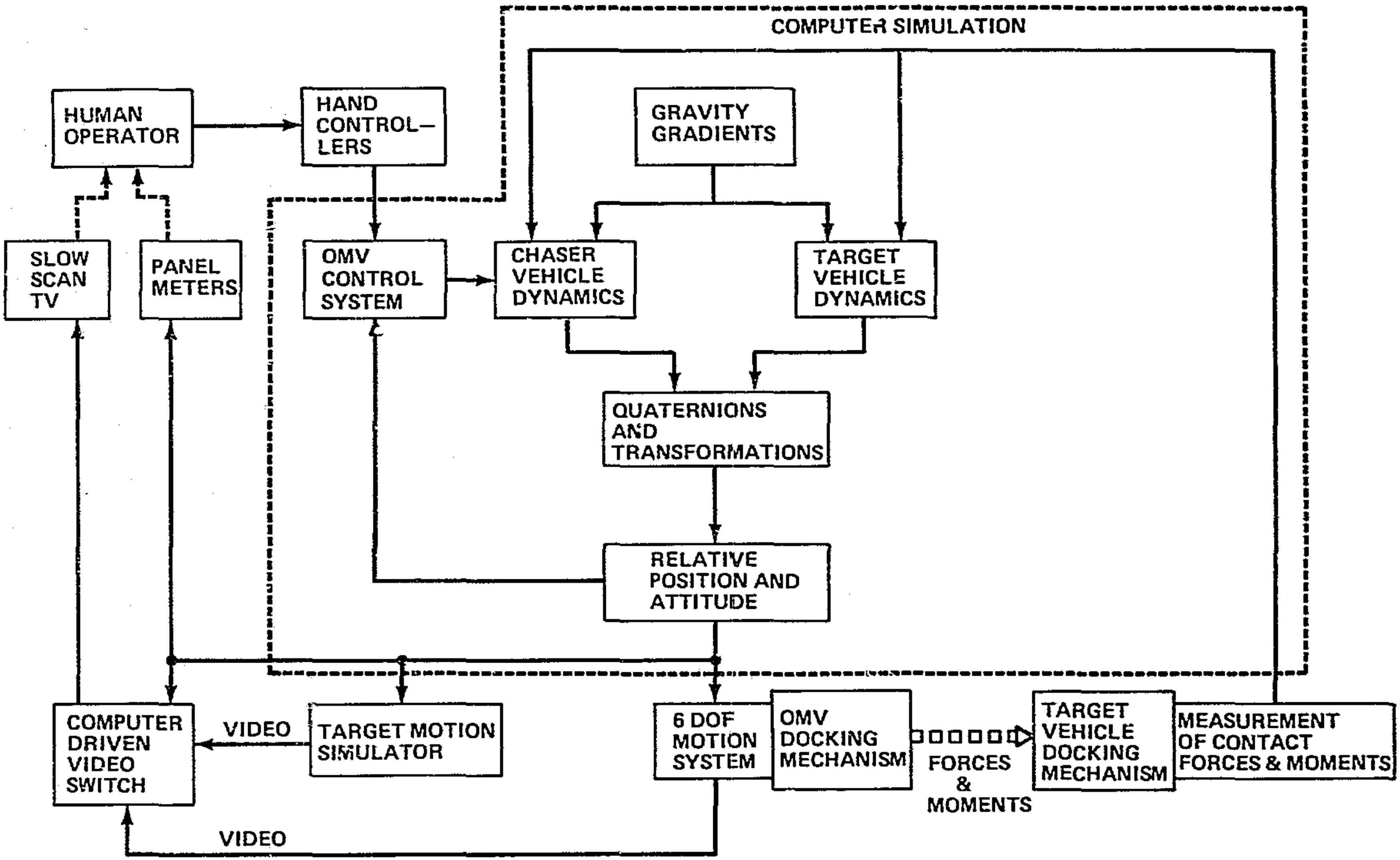


Figure 7. OMV orbital docking simulation.

a) Radar range

b) Radar range rate

c) RCS fuel expended

d) Ground Control Station (GCS) roll rate commands

e) GCS yaw rate commands

f) GCS pitch rate commands

g) OMV roll rate response

h) OMV yaw rate response

i) OMV pitch rate response.

An auxiliary program was also developed to provide data analysis. It consisted of approximately 2300 lines of code to collect specified simulation variables and insert this into a data base. It also provided off-line data analysis and plotting of test subject performance.

C. Target Motion Simulator

The TMS provided video images, in six degrees-of-freedom, of the target vehicle as viewed by the OMV docking TV camera. The TMS consisted of a three-axis gimbal system for a TV camera and a second three-axis gimbal system containing a scale model of the target vehicle. The model gimbal system translated on a horizontal rail to represent closure of the OMV to the target. Figure 8 is a photograph of the TMS showing the camera gimbal on the left and the target gimbal on the right. Performance of the TMS is tabulated in Figure 9. Note that the linear motion performance is determined by the scale selected for the model.

The target vehicle utilized in this simulation was a Landsat D scaled 1/12 in size. This model included a precision machined representation of the grapple fixture and associated alignment aid. The model was not configured for extended antennas or solar panels. Since the model was illuminated with uniform lighting in the TMS, the effect of sun location and resultant shadows was absent. Lighting conditions more representative of actual orbital operations may either enhance or detract from the capability of remote controlled docking.

PILOT TRAINING

The four subjects used for this study were selected from seven test subjects who trained in a recent orbital docking simulation exercise. The training period consisted of three 1-hr sessions. A common set of training instructions was provided to each test subject and at the conclusion of this training a debriefing was made of each test subject. The seven subjects were grouped according to their experience flying the simulator. Before this training exercise, subjects 1 and 3 had flown the orbital docking simulator. Subjects 1, 2, and 4 had airplane flying experience. Subject 1 had a Private Pilot license and 4 had a Commercial Pilot license.

The plots and other information from this study may be viewed in the Appendix.

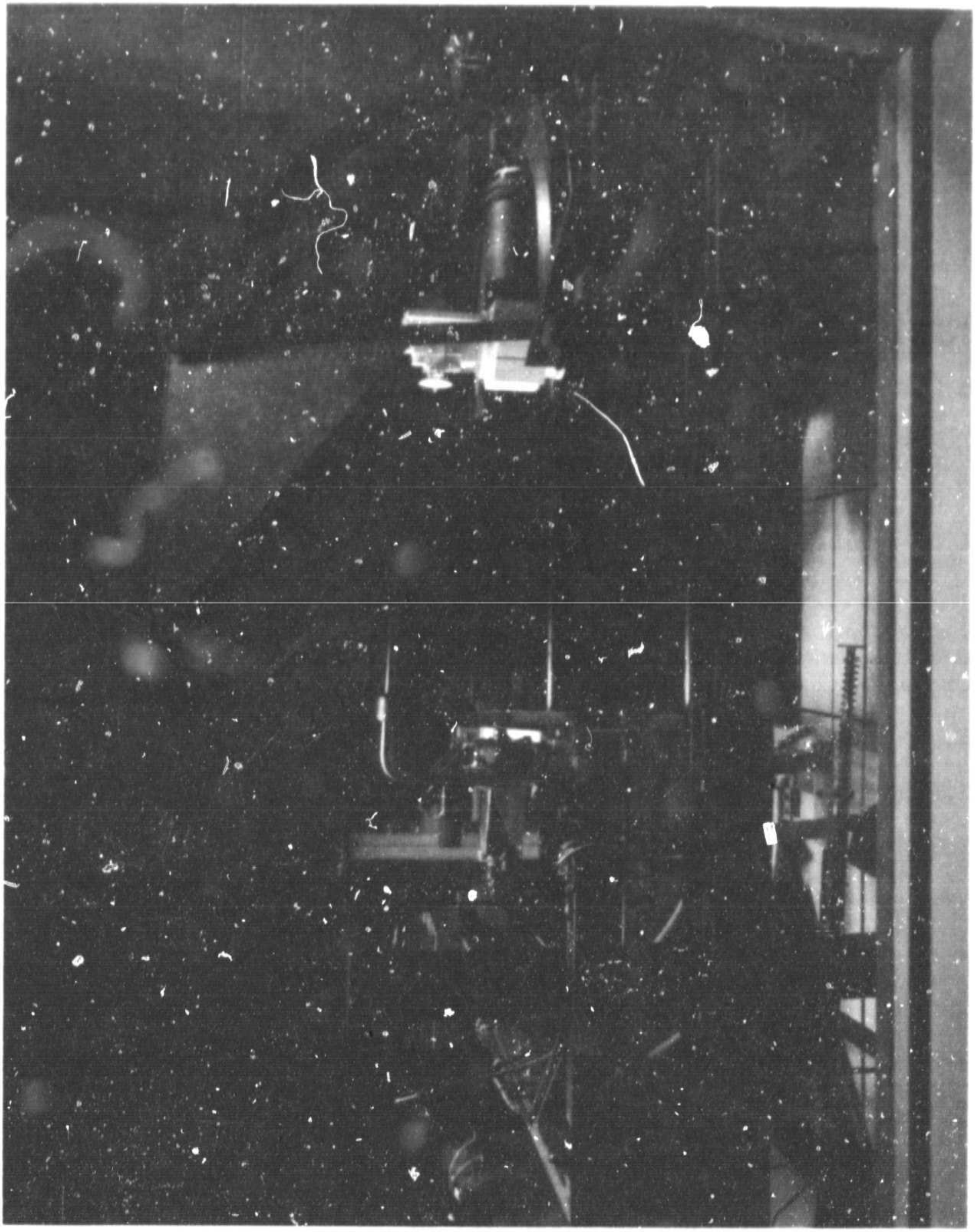


Figure 8. Target Motion Simulator (TMS).

MOTION SERVO	POSITION TRAVEL	POSITION ACCURACY	MAXIMUM VELOCITY
TARGET ROLL	±180 DEG. *	±1/2 DEG.	±50 DEG./SEC.
TARGET YAW	±90 DEG.	±1/2 DEG.	±10 DEG./SEC.
TARGET PITCH	±90 DEG.	±1/2 DEG.	±10 DEG./SEC.
CAMERA ROLL	±180 DEG.	±1 DEG.	±75 DEG./SEC.
CAMERA YAW	±90 DEG.	±1/4 DEG.	±5 DEG./SEC.
CAMERA PITCH	±90 DEG.	±1/2 DEG.	±5 DEG./SEC.
LINEAR MOTION (FOR 1/12 SCALE MODEL)	APPROX. 100 FT.	±2 IN. (FOR 1/12 SCALE MODEL)	±25 FT./SEC.

Figure 9. Performance of TMS.

PILOT COMMENTS

Debriefings of the four test subjects were conducted at several stages throughout this study. Cooper-Harper ratings, depicted in Figure 10, were used once to quantify the test subject's opinion of the handling characteristics for this particular OMV simulation. These ratings were taken after initial simulation runs and varied as follows:

Subject 1 rated the system a 3 or 4

Subject 2 rated the system a 3

Subject 3 rated the system a 2

Subject 4 rated the system a 4 or 5.

1	EXCELLENT; HIGHLY DESIRABLE
2	GOOD; NEGLIGIBLE DEFICIENCIES
3	FAIR; SOME MILDLY UNPLEASANT DEFICIENCIES
4	MINOR BUT ANNOYING DEFICIENCIES
5	MODERATELY OBJECTIONABLE DEFICIENCIES
6	VERY OBJECTIONABLE BUT TOLERABLE DEFICIENCIES
7	MAJOR DEFICIENCIES
8	MAJOR DEFICIENCIES
9	MAJOR DEFICIENCIES
10	WORSE CASE OF MAJOR DEFICIENCIES

Figure 10. Cooper-Harper rating scale for aircraft flying qualities.

Comments on the attitude rate hold mode revealed that this feature could be useful for target vehicle rotation on one axis. However, when the target rotated about multiple axes, the attitude rate hold mode – as currently implemented – was troublesome for some pilot operations. It was generally agreed that this mode was necessary for those cases of higher target rotation rates. One subject suggested, as a possible emergency feature, a dump button to immediately remove those attitude rates that had previously been entered for a rate hold. When asked their opinion of the commercial transport pilot's seat, the subjects found it to be satisfactory but not exceptional. All agreed that the adjustable capability and stability was better than the computer operator's chair used for training sessions. The run time of 1 hr seemed to satisfy all subjects. Although fatigue surfaced within the 1-hr period, the subjects stated that running for a shorter period of time would not be beneficial. The fatigue most experienced was a tired wrist which increased for the higher target rotation rates. Comments on the location, size and use of the displays were unanimous: Each subject stated they were adequate. For the runs completed with radar information, the subjects definitely depended on and used the available information. But without radar information, the subjects stated they concentrated on the TV monitor view of the target. For these cases they felt that they made fewer mistakes by not shifting their eyes from the TV monitor to the range and range rate displays. When asked if displaying the radar information on the screen would make a difference, one subject stated that it would still be a distraction. Additional test subject comments included reducing the thruster size from 15 lb in order to have better control during the final few feet of docking, or having pulse width control of the thrusters for better docking accuracy.

RESULTS

A. Description of Data

The following list defines the end conditions chosen as the indices of performance:

1) $(\text{DELTA}(Y), \text{DELTA}(Z))^{RSS}$ – Root-sum-squared of the chase to target vehicle attitude errors in pitch and yaw at dock.

2) $(\text{DPDS}(Y), \text{DPDS}(Z))^{RSS}$ – Root-sum-squared of the chase to target vehicle translation offsets in the Y- and Z-axes at dock.

3) DELTA(X) – Chase to target vehicle roll error at dock.

4) $(\text{DPDSD}(Y), (\text{DPDSD}(Z))^{RSS}$ – Root-sum-squared of the chase to target vehicle translational rates in the Y- and Z-axes at dock.

5) DPDSD(X) – Chase to target vehicle closing velocity (X direction) at dock.

6) Total Firing – Accumulated firings of the RCS engines.

7) Fuel Expended – Amount of fuel used, measured in pounds.

8) Elapsed Time – Time in seconds to perform dock.

These end conditions are summarized in tabular form in Figures 11 through 14. Plots of the raw data are included in the Appendix. Each plot contains the results of all three radar complements plotted against target vehicle tumbling rates. Only the data from successful runs (runs where the pilot met the

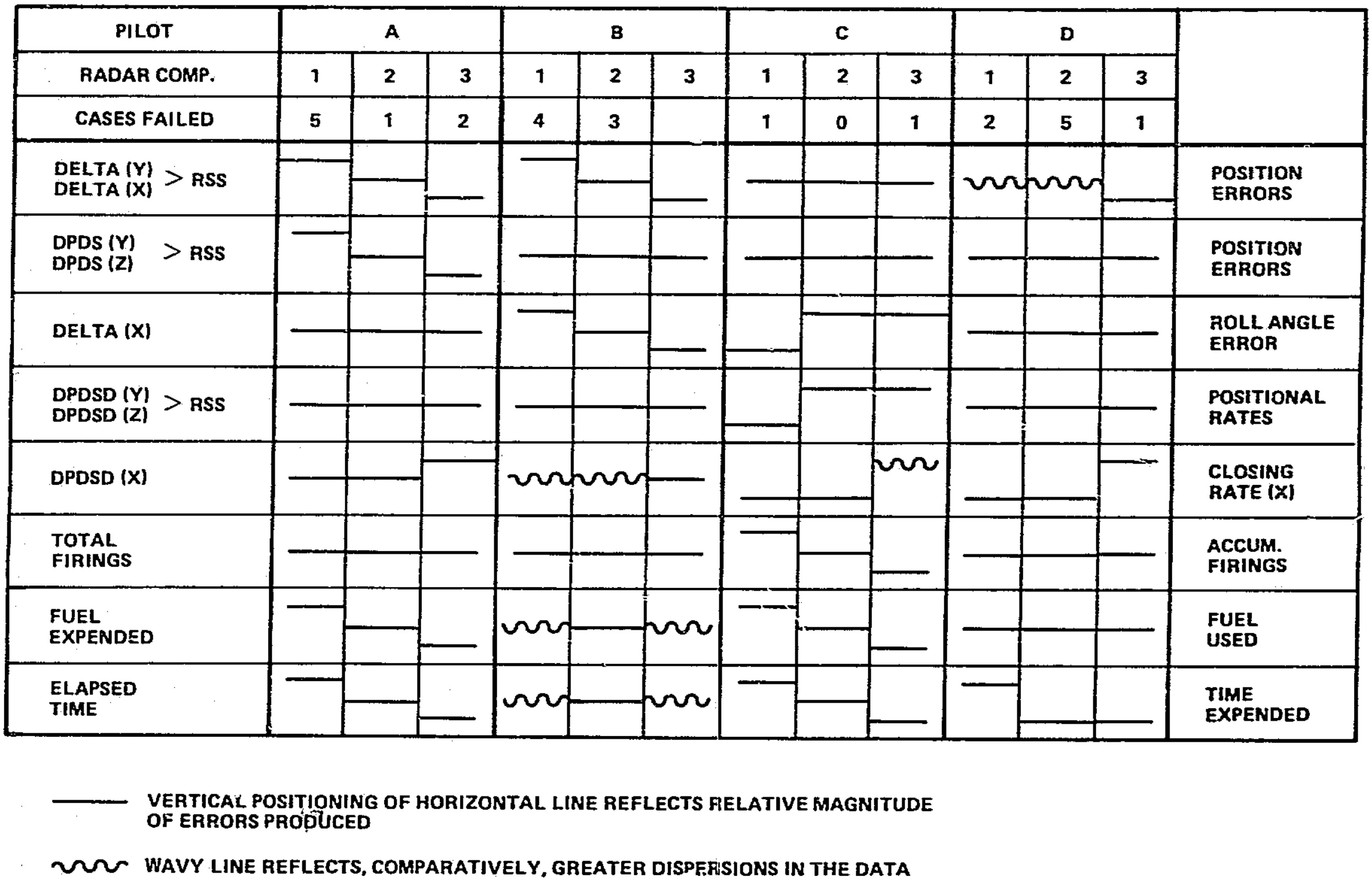


Figure 11. Cases with target roll rate.

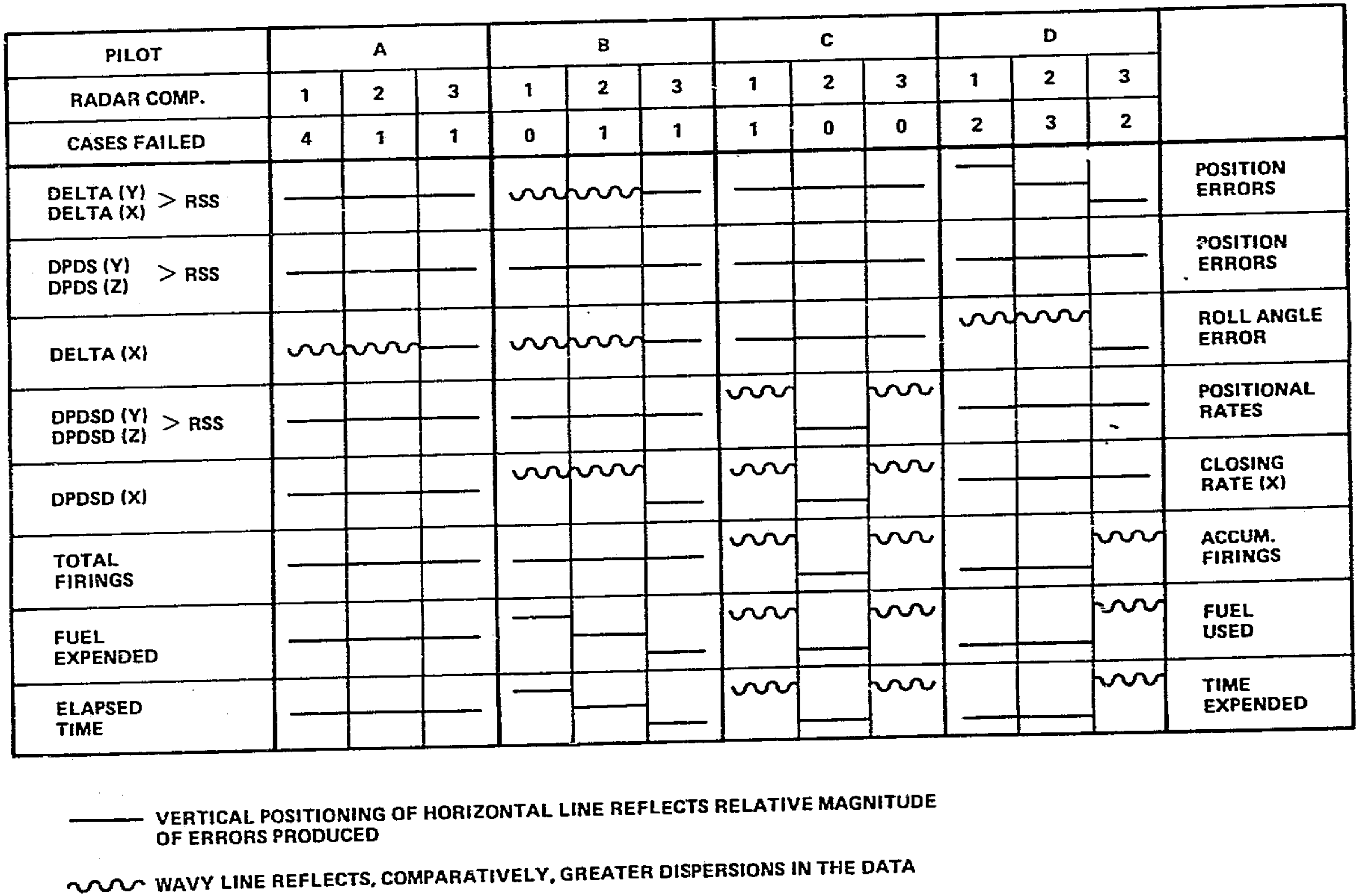
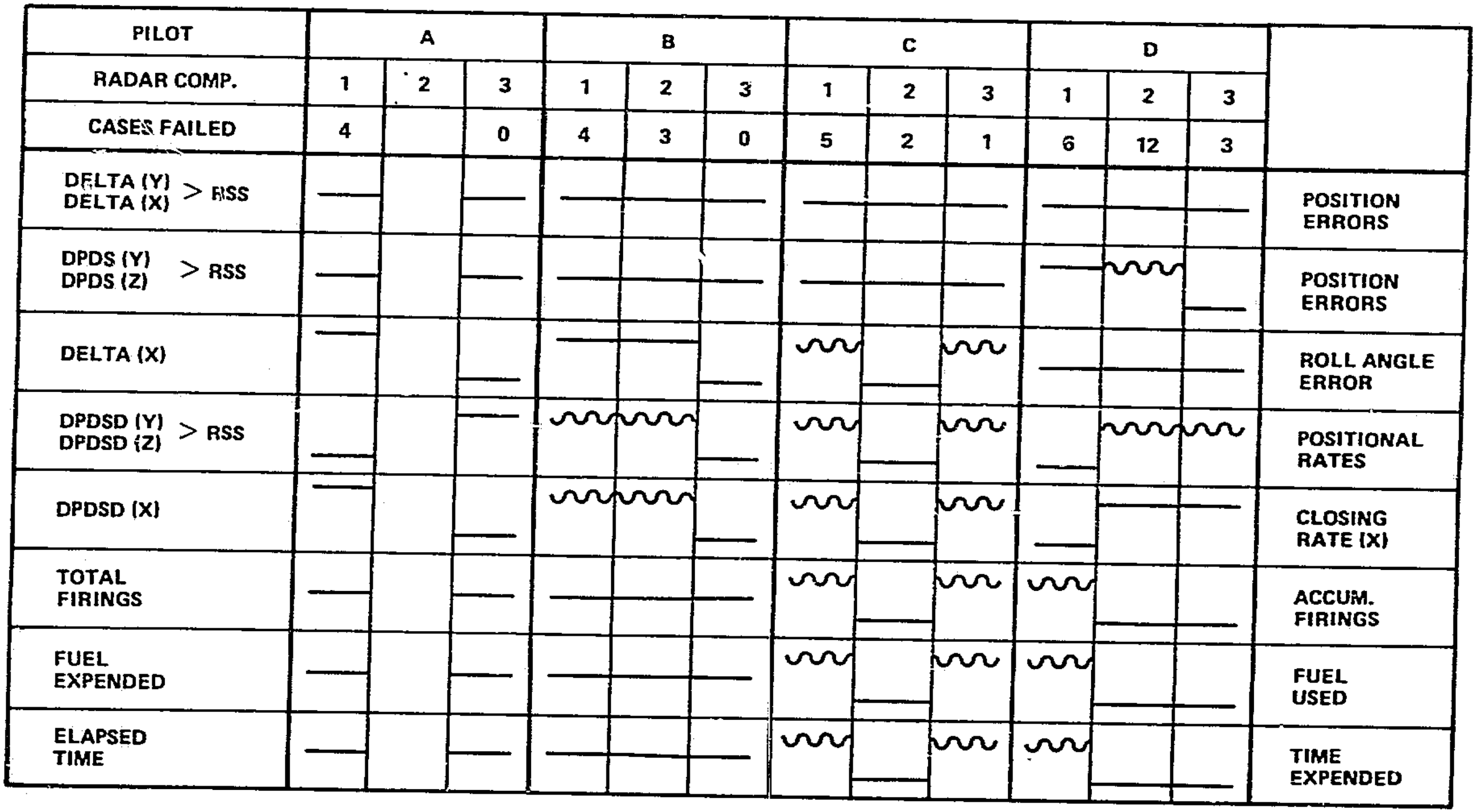


Figure 12. Cases with target pitch rate.



—— VERTICAL POSITIONING OF HORIZONTAL LINE REFLECTS RELATIVE MAGNITUDE OF ERRORS PRODUCED

∿∿ WAVY LINE REFLECTS, COMPARATIVELY, GREATER DISPERSIONS IN THE DATA

Figure 13. Cases with rates on all target axes.

	ROLL				PITCH				ROLL–PITCH–YAW				
TUMBLE AXIS	X				Y				X–Y–Z				
PILOT	A	B	C	D	A	B	C	D	A	B	C	D	
DELTA (Y) DELTA (Z) > RSS	/	—	/	—	/∿	—	/	\	/∿	/	—	—	POSITION ERRORS
DPDSD (Y) DPDSD (Z) > RSS	—	—	/	—	/	/	—	∿	/∿	—	∿	—	POSITION ERRORS
DELTA (X)	/	/	∿	/	—	—	—	—	/	—	∿	—	ROLL ANGLE ERROR
DPDS (Y) DPDS (Z) > RSS	/	—	—	/∿	/∿	/	∿	\	/	/∿	/	/	POSITIONAL RATES
DPDSD (X)	—	—	—	/	/	/∿	\	—	—	/∿	∿	/	CLOSING RATE (X)
TOTAL FIRINGS	/	/	/	—	/	/	—	/	/	/∿	∿	—	ACCUM. FIRINGS
FUEL EXPENDED	/	/	/	/	/	/∿	/	/	/	/∿	∿	—	FUEL USED
ELAPSED TIME	/∿	/	/	—	/	/∿	—	/	/	/∿	∿	—	TIME EXPENDED

/ DENOTES UPWARD TREND

— DENOTES NO APPARENT TREND

\ DENOTES DOWNWARD TREND

∿ DENOTES INCREASED DISPERSIONS IN DATA

Figure 14. Effects of increasing target vehicle tumbling rates.

docking envelope requirements) were plotted. The numbers on the plots above the curves represents the number of unsuccessful docking attempts incurred for that particular radar complement at that specified target vehicle tumbling rate.

B. Data Analysis (Radar)

The affects of varying the radar complement on the docking end conditions are summarized in Figures 11 through 13 for cases with target roll rate, target pitch rate, and target rates on all axes, respectively. The three radar complements investigated were:

1) Complement 1 – Range and range rate displayed to pilot.

2) Complement 2 – Range rate displayed to pilot.

3) Complement 3 – No radar information displayed to pilot.

Comparative results of these three complements are summarized with a graphical scheme using varying combinations of horizontal straight and horizontal wavy lines. For a given pilot and end condition variable, the relative height of each horizontal line represents the relative magnitude obtained, on average, for that particular end condition. A wavy line indicates larger variations in results obtained, from run to run. Two examples are included for illustration:

EXAMPLE 1: Reference Figure 11, cases with target roll rate, Pilot A and end conditions of elapsed time.

```
PILOT                    A
--------------------------------
RADAR COMP      1        2      3
--------------------------------
CASES FAILED    5        1      2
--------------------------------

                ---                      <---- Level 1
ELAPSED                 ---              <---- Level 2
TIME                          ---        <---- Level 3
--------------------------------
```

Interpretation: For cases with target roll rate only, pilot A took the most time to dock on average with radar Complement 1 (Level 1), less time with Complement 2 (Level 2) and the least time with Complement 3 (Level 3).

EXAMPLE 2: Reference Figure 11, cases with target roll rate, Pilot C and end condition, closing rate.

```
PILOT                    C
--------------------------------
RADAR COMP        1      2      3
--------------------------------
CASES.FAILED      1      0      1
--------------------------------

DPDSD (X)                ~~~~~~          <---- Level 1
(CLOSING RATE     ------                 <---- Level 2
--------------------------------
```

Interpretation: First, Pilot C produced higher closing rates with radar Complement 3 (Level 1). Secondly, Pilot C produced larger swings in the data (indicated by wavy line) from run to run with Complement 3. Thirdly, comparable results were obtained from Pilot C when using radar Complements 1 and 2 as evidenced by the straight horizontal lines at Level 2.

Review and analysis of the data in much the same way as illustrated in the above two examples leads to the following observations/conclusions with regard to pilot performance and the effects of varying complements of radar:

1) Pilot C, the most proficient pilot in terms of docking accuracies, number of failure cases and ability to accommodate higher target tumbling rates, produced superior end conditions overall with radar Complement 2 (range rate only).

2) Pilots A and B produced better results overall with radar Complement 3 (no range or range rate displayed). Though it would be wrong to attribute this entirely to learning curve, there is strong evidence of the learning curve effect on their data. See Pilot A's summary in Figure 11 and Pilot B's summary in Figure 12 where the improvement in pilot's performance clearly coincides with the experiment chronology.

3) Pilot D's results show no consistent preference for any one particular radar complement. Having the least experience of the four pilots, Pilot D's results evidence more failure cases and more "scatter" in the test results.

4) A hard requirement for radar for the closure and dock phase of OMV mission was not established with this study, but it should be noted that a maximum closing velocity was not part of the docking success criteria. Though closing velocities were moderate (less than 0.25 ft/sec in most cases), additional study would be required to determine the pilot's ability to estimate and maintain closing rates at maximum closing rates of less than 0.25 ft/sec, especially with regard to accommodating dynamic target engagements.

C. Data Analysis (Tumbling Target)

The effects of varying target vehicle tumbling rates on the docking end conditions are summarized in Figure 14. A graphical scheme similar to that described above has been employed. However, in this case, the "straight or wavy line" pertains to a given pilot and end condition where the slope of the line reflects the propogative trend of the end condition as the target spin rates are increased. The following example illustrates this graphical scheme:

EXAMPLE 3: Reference Figure 14

TUMBLE AXIS	X
PILOT	A
DELTA (Y)	/
DELTA (Z)	~

Positive Slope – Upward Trend
Wavy Line – Larger Data Swings

Interpretation: For cases with target roll rate (only), Pilot A produced an upward trend on Y- and Z-axis positional errors as the target roll rates were increased. In addition, the wavy line indicates larger variations in errors also resulted.

Analysis of the raw data as well as the tabulated summary described above supports the above appraisal of individual pilot performance. Though absolute maximum target tumble rates were not determined, the data further suggests the following:

1) Cases with target roll rate only were but moderately more difficult than stabilized target cases. Rates in excess of 2 deg/sec may be attainable.

2) Cases with target pitch rate only were more difficult for the pilots to handle because chase to target vehicle rate matching requires a combination and coordination of translational and rotational maneuvers. Though absolute limits were probably not established, there was a clear demarcation in the results for all pilots at pitch rates approaching 1 deg/sec.

3) Cases with rates on all target axes were markedly more difficult for the pilot to accommodate. Chase to target vehicle rate matching with a target vehicle undergoing a coning motion requires that the pilot fly a spiraling trajectory during the closure phase. Larger errors and more docking failures were recorded for these cases and there were greater dispersions in the end condition data collected. Though additional study/simulation is needed to establish the pilot's ability to dock with target vehicles undergoing coning, the results of this study suggest that target vehicle rates of 0.5 deg/sec in all axes could be achievable.

CONCLUSION

Both the radar and the tumbling target parameters will be visited with future simulations. But with the current study results, some conclusions can be drawn. For example, for stabilized target engagements, results indicate no requirement for displaying range and/or range rate information to the pilot during the docking sequence. However, the most experienced and proficient pilot in our test produced better results with range rate information displayed when flying cases with dynamic targets. The magnitude of the target vehicle rates to which the pilot can accommodate depends on the kind and number of target vehicle axes involved. Target rates from 0.5 deg/sec (with all axes involved) up to rates greater than 2 deg/sec (with roll rates only) can be accommodated. These results/conclusions are consistent with those found from simulation studies conducted during the Teleoperator Retrieval System (TRS) program with the flight crew both in terms of the effects of range/range rate data and in terms of the effects of dynamic targets on the pilot's ability to fly the closure and dock phase of flight.

The MSFC baseline OMV configuration and point-design man-in-the-loop control system performed well. Fifteen pound thrusters showed advantage in chase to target vehicle rate matching maneuvers as did the rate hold feature on the rate proportional stick. After the target rates have been matched, prior to final closure, however, a low thrust mode was considered to have been desirable in making final adjustments to the chase vehicle position. As a result, lower thrust levels and/or switch selectable low thrust modes will be incorporated into the next simulation study. Changes made to the OMV configuration and to the man-in-the-loop control system will affect pilot performance and produce variations in simulation results. Consequently, a series of simulation studies will be required to address those issues of importance for the OMV program, in general, and for the control system design process, in particular. This study is the first in that series planned for FY-85.

REFERENCES

1. Teleoperator Maneuvering System Preliminary Definition Study. Prepared by Program Development, June 1983.

2. Software Specifications for Docking Simulation of the Orbital Maneuvering Vehicle. ED15-83-64, January 11, 1984.

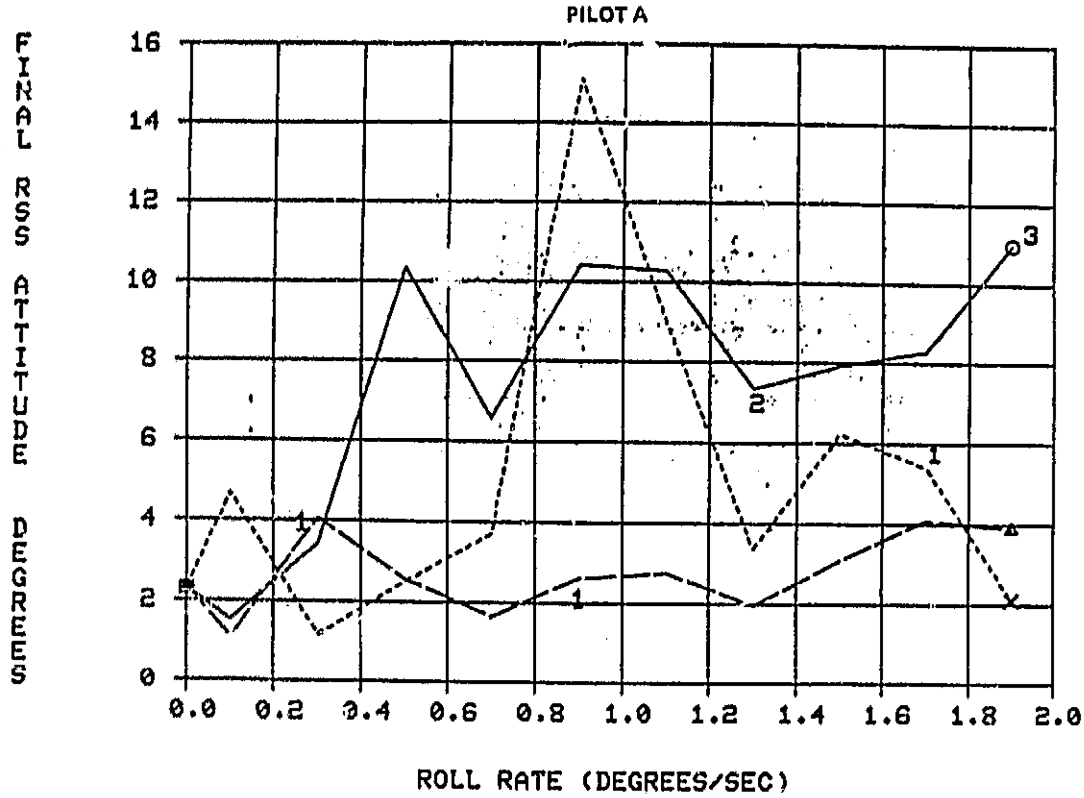
3. Random Initial Condition Generator for the TMS. ED-15-84-31, October 29, 1984.

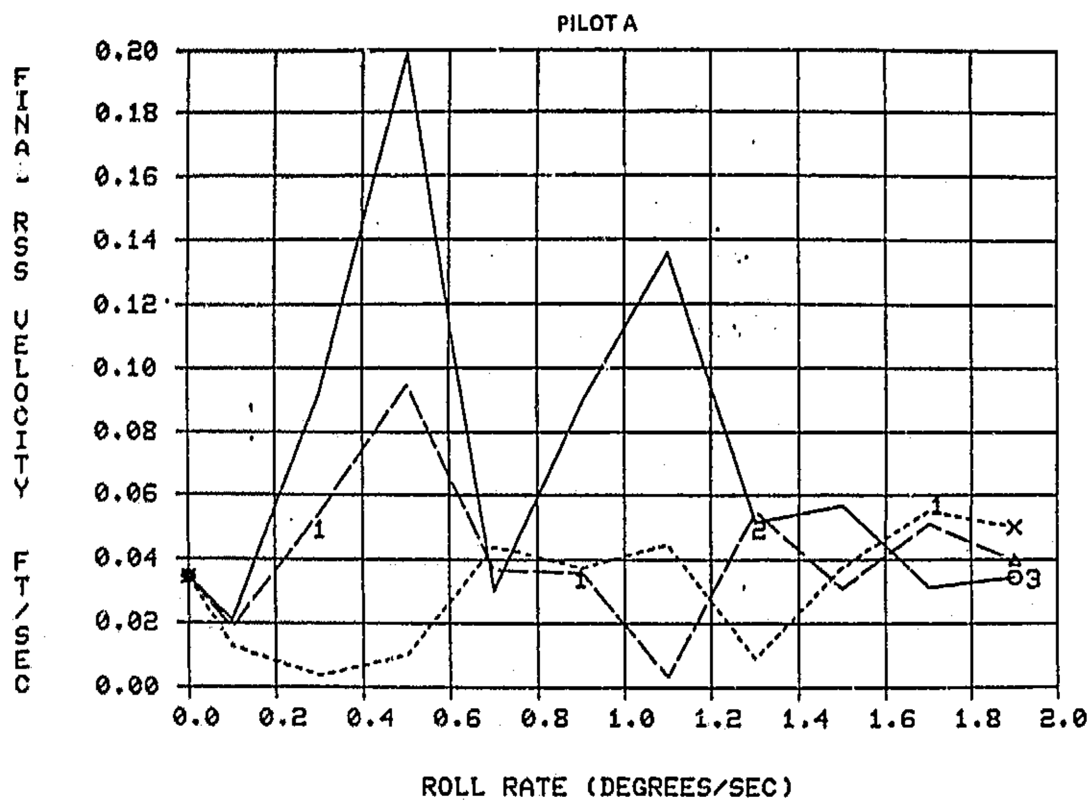
4. Orbital Maneuvering Simulation Study Report, EL15 (163-84), October 2, 1984.

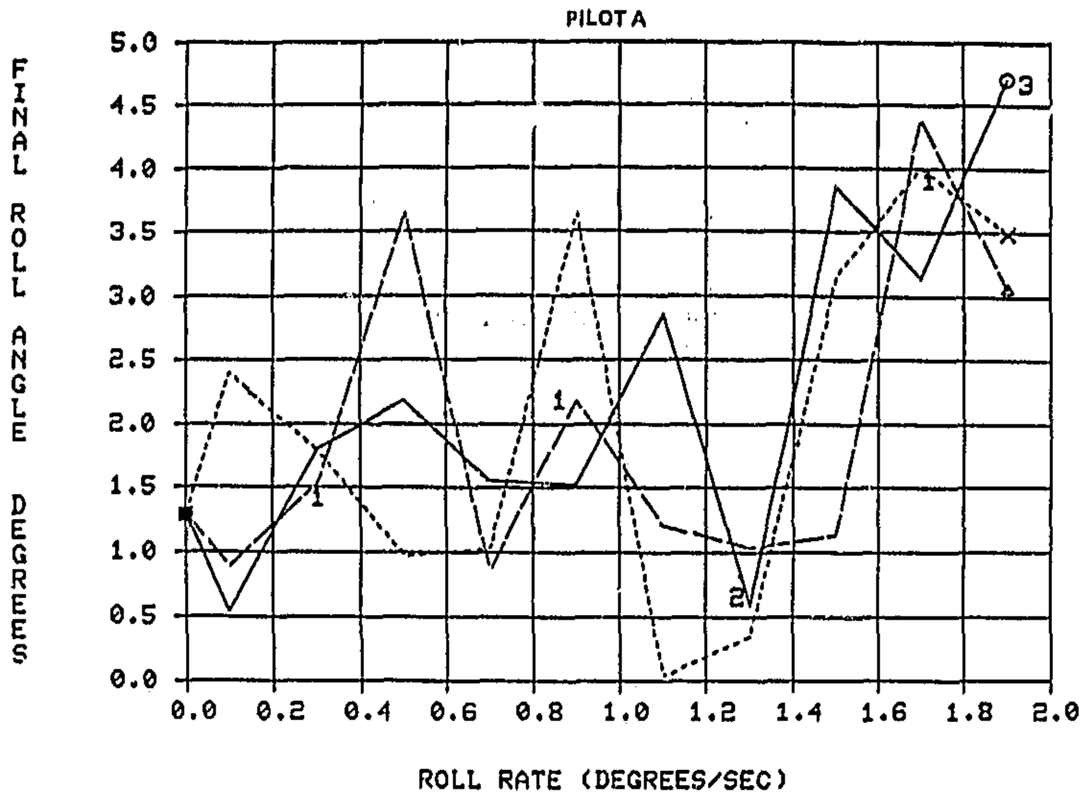
APPENDIX

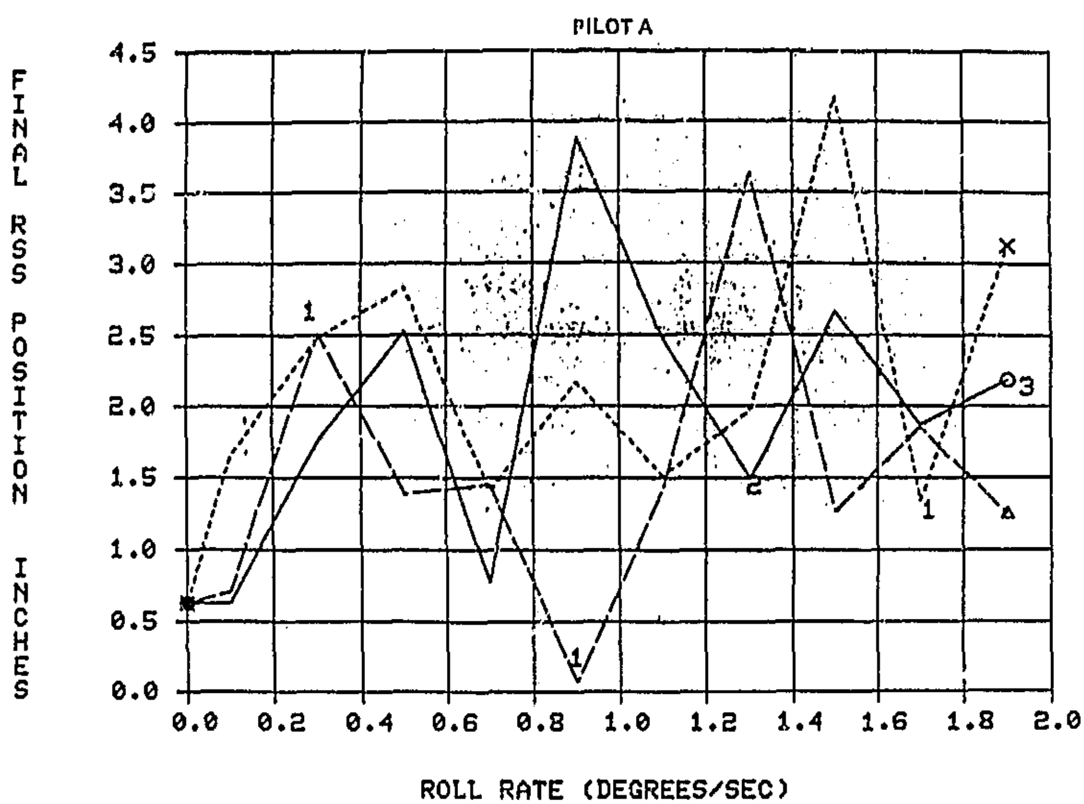
The following legend applies for each graph in the appendix.

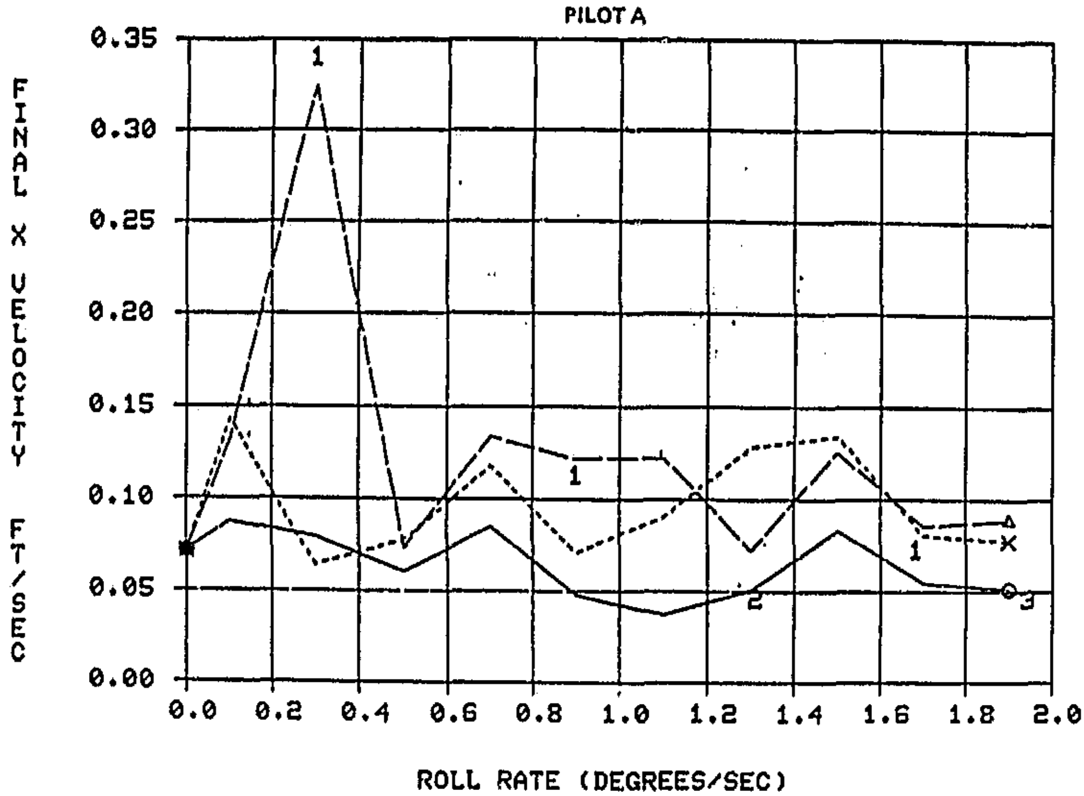
——— Radar Range and Range Rate
– – – – Radar Range Only
· · · · · · No Radar

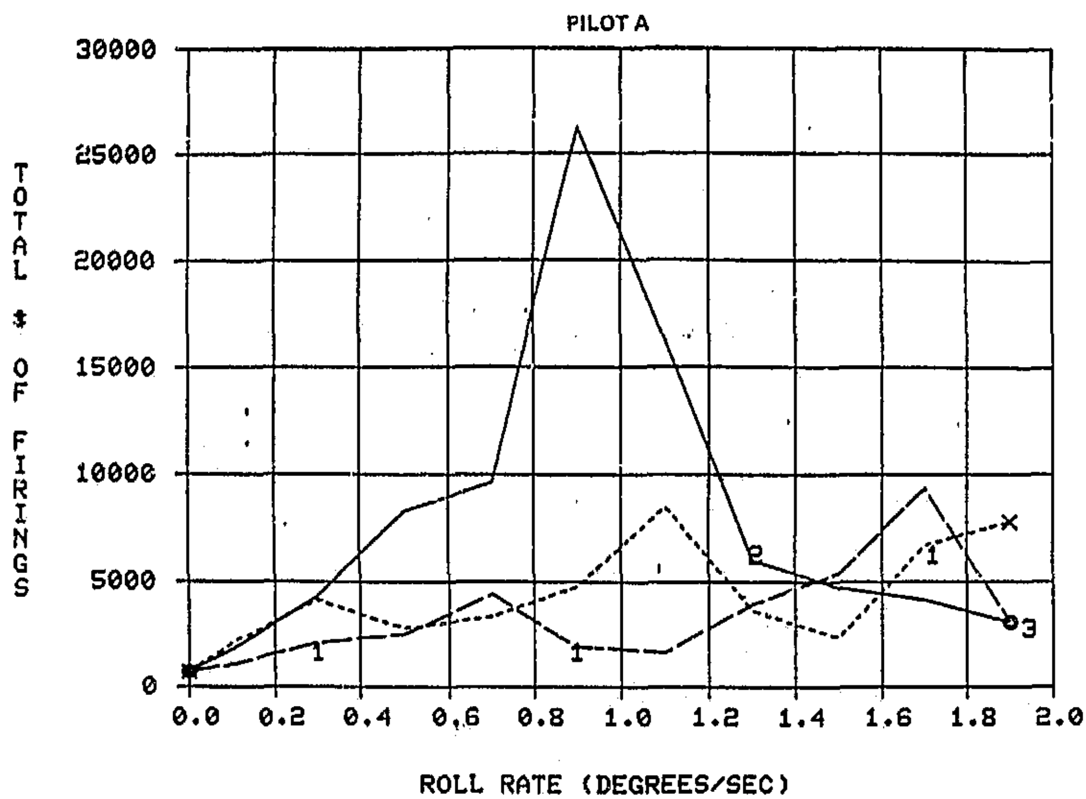


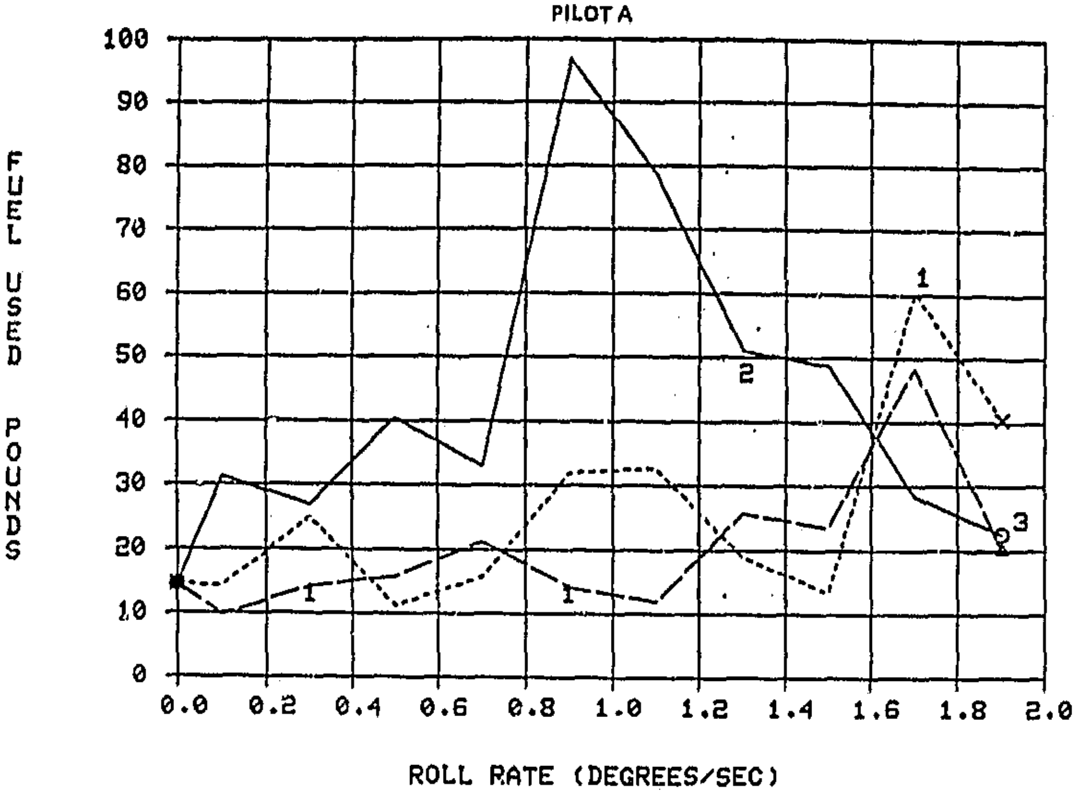


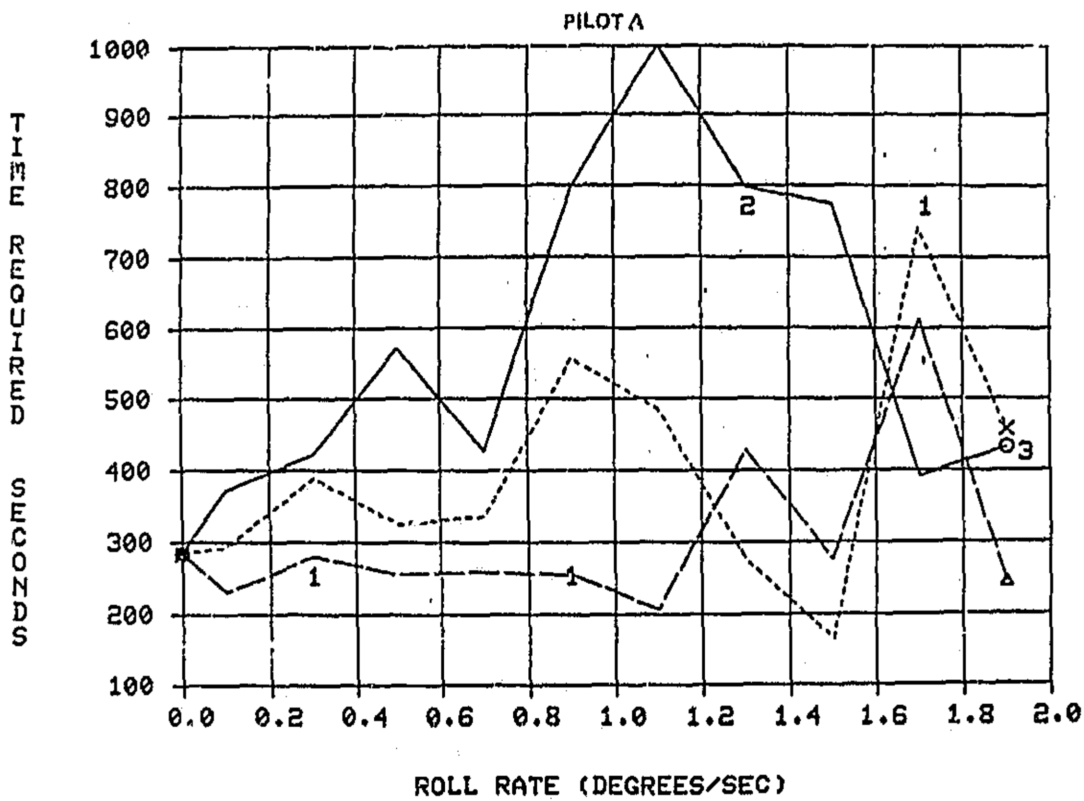

PILOT A
FINAL ROLL ANGLE DEGREES
ROLL RATE (DEGREES/SEC)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
1
2
3

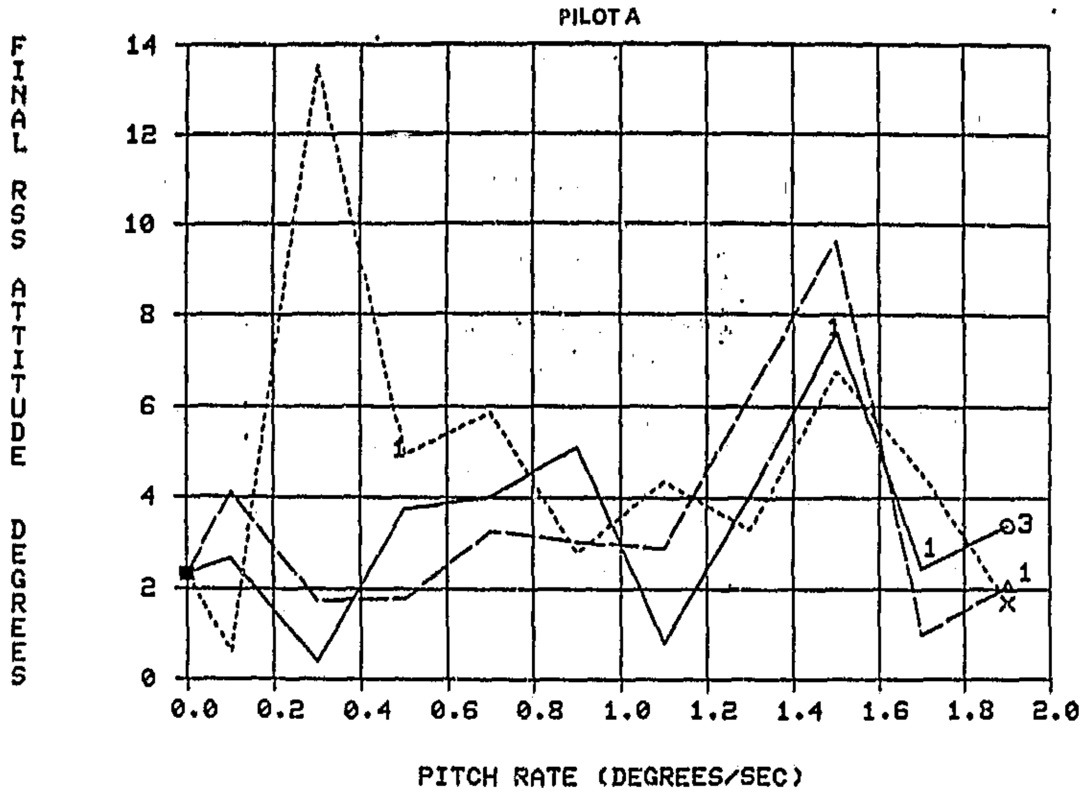

PILOT A
FINAL RSS POSITION INCHES
ROLL RATE (DEGREES/SEC)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
1
2
3

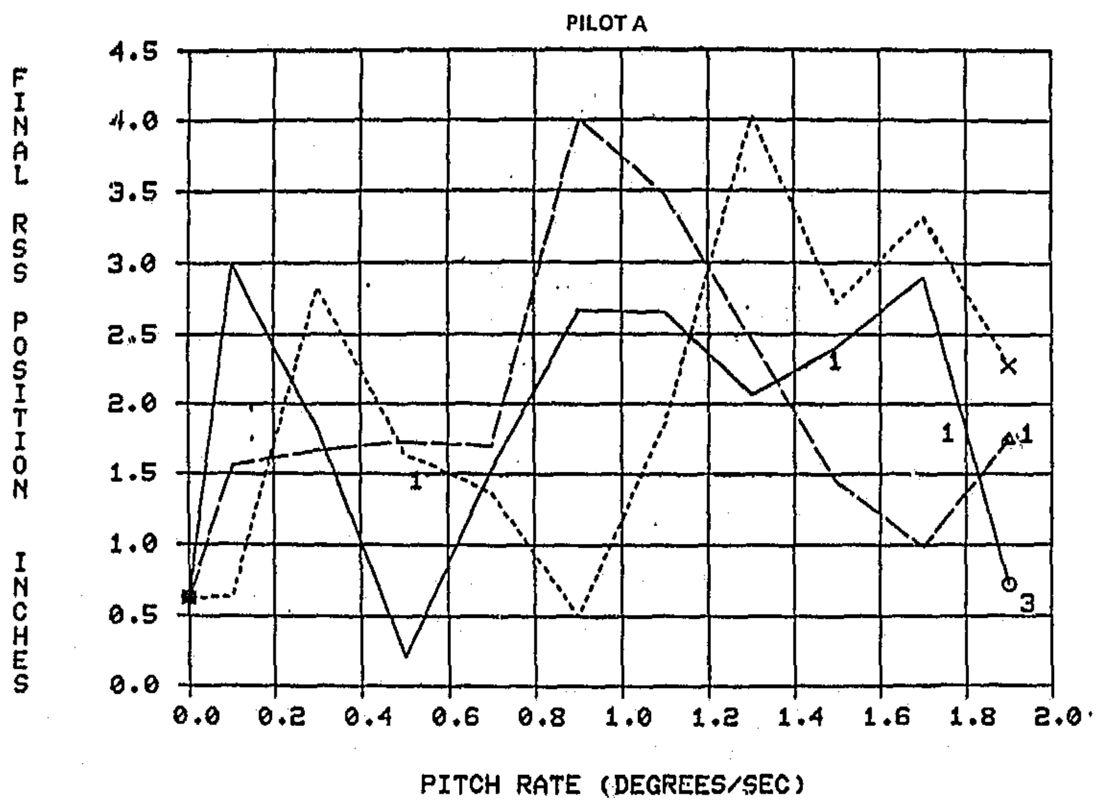

PILOT A
FINAL X VELOCITY FT/SEC
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)

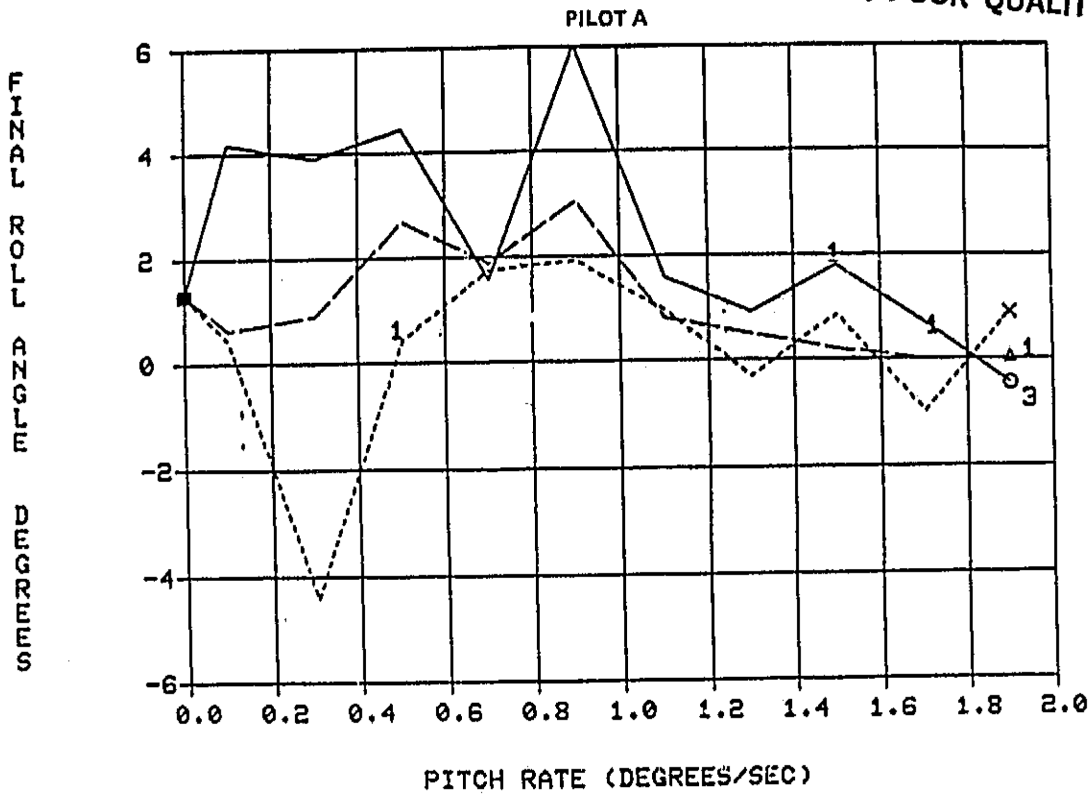

PILOT A
TOTAL # OF FIRINGS
30000
25000
20000
15000
10000
5000
0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)

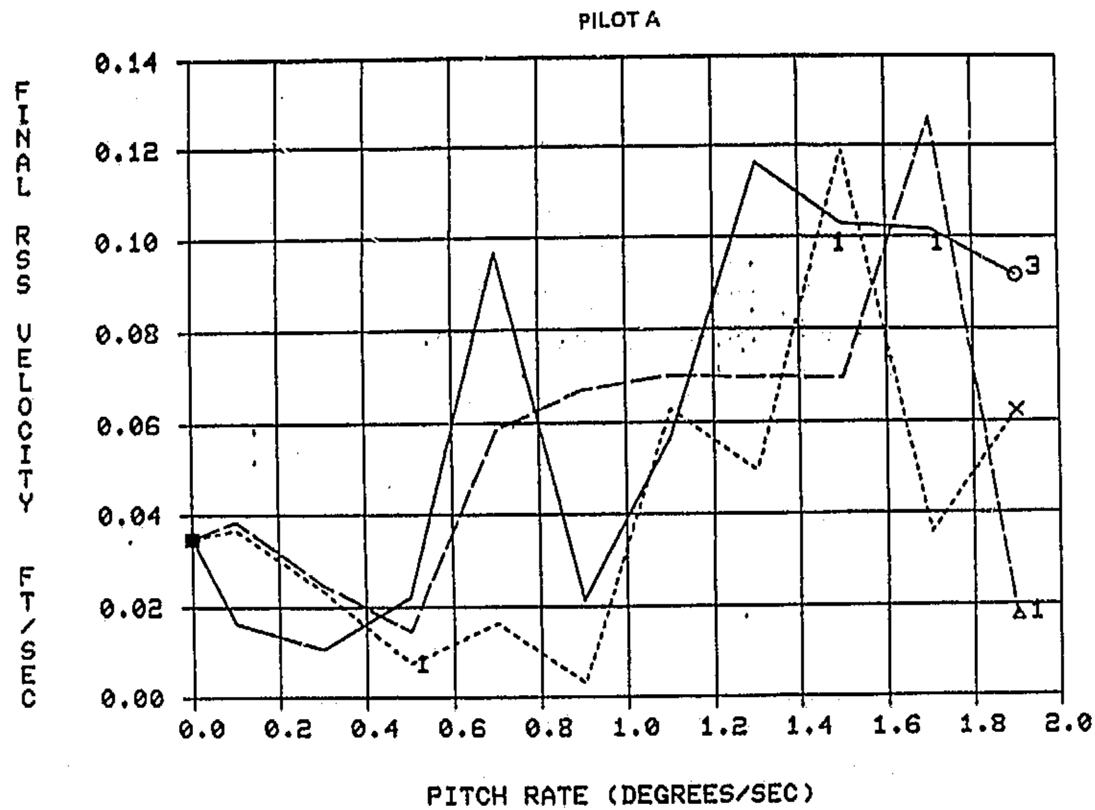

PILOT A
FUEL USED POUNDS
100
90
80
70
60
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)
1
2
3


PILOT A
TIME REQUIRED SECONDS
1000
900
800
700
600
500
400
300
200
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)
1
2
3

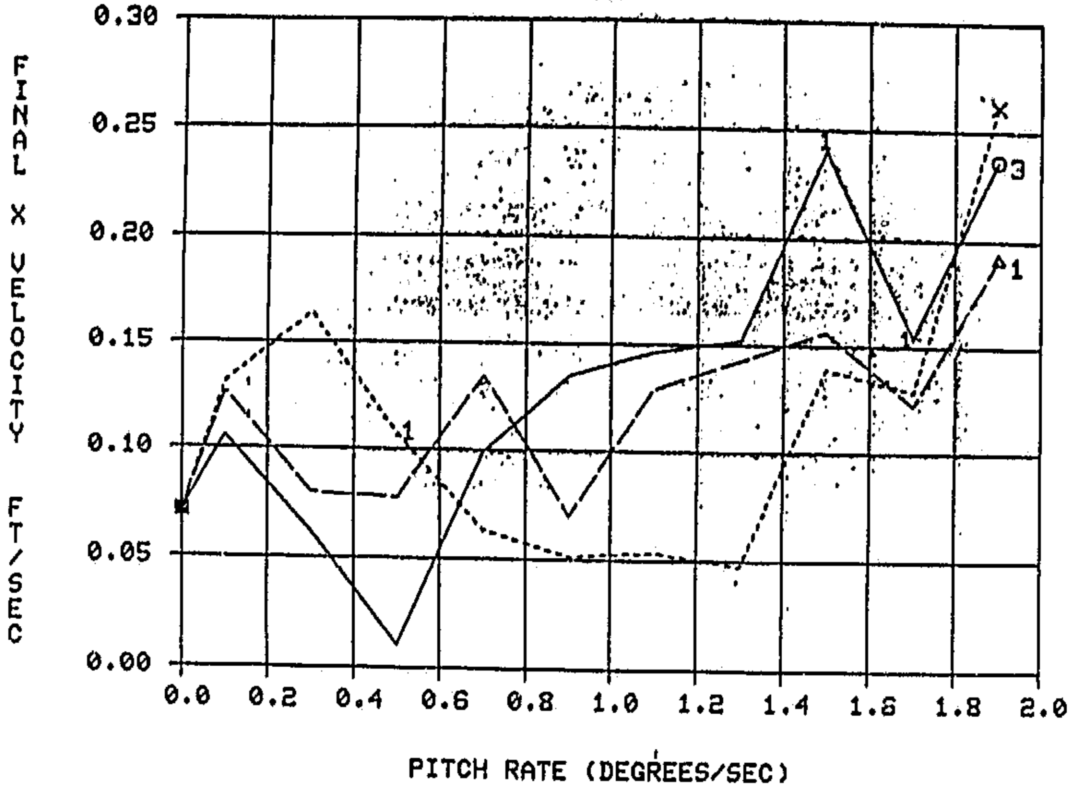

PILOT A
FINAL RSS ATTITUDE DEGREES
14
12
10
8
6
4
2
0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)
1
3


PILOT A
FINAL RSS POSITION INCHES
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)
1
3

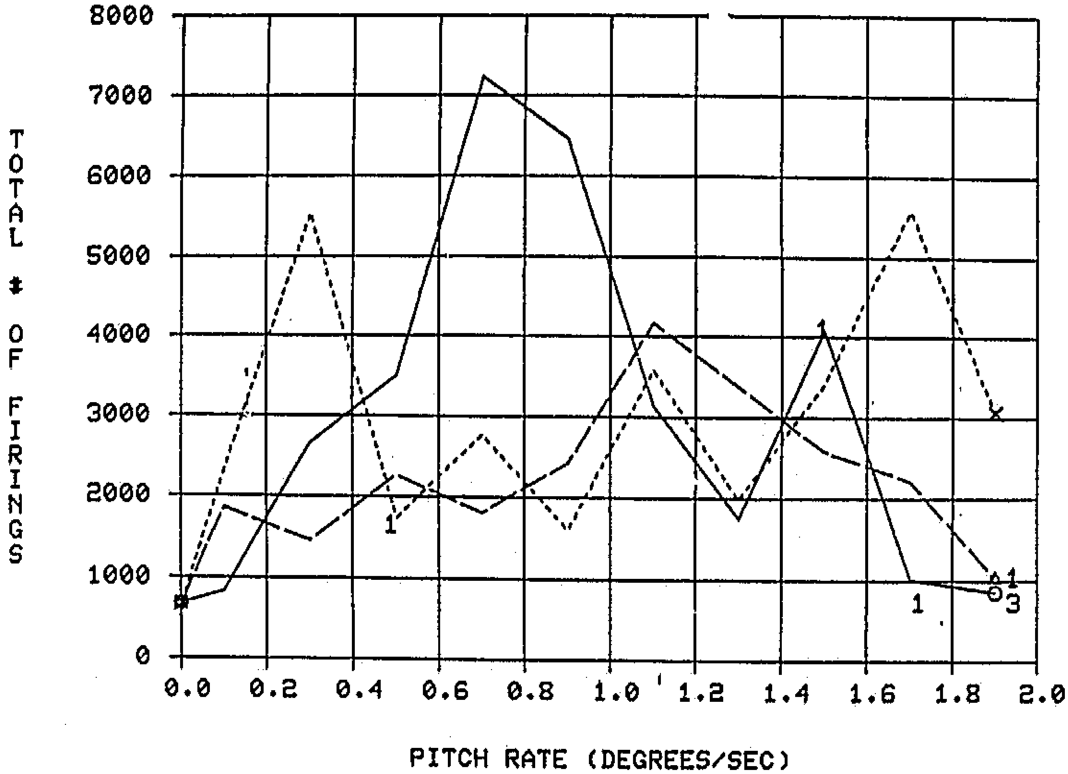

PILOT A
FINAL ROLL ANGLE DEGREES
6
4
2
0
-2
-4
-6
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)
1
3

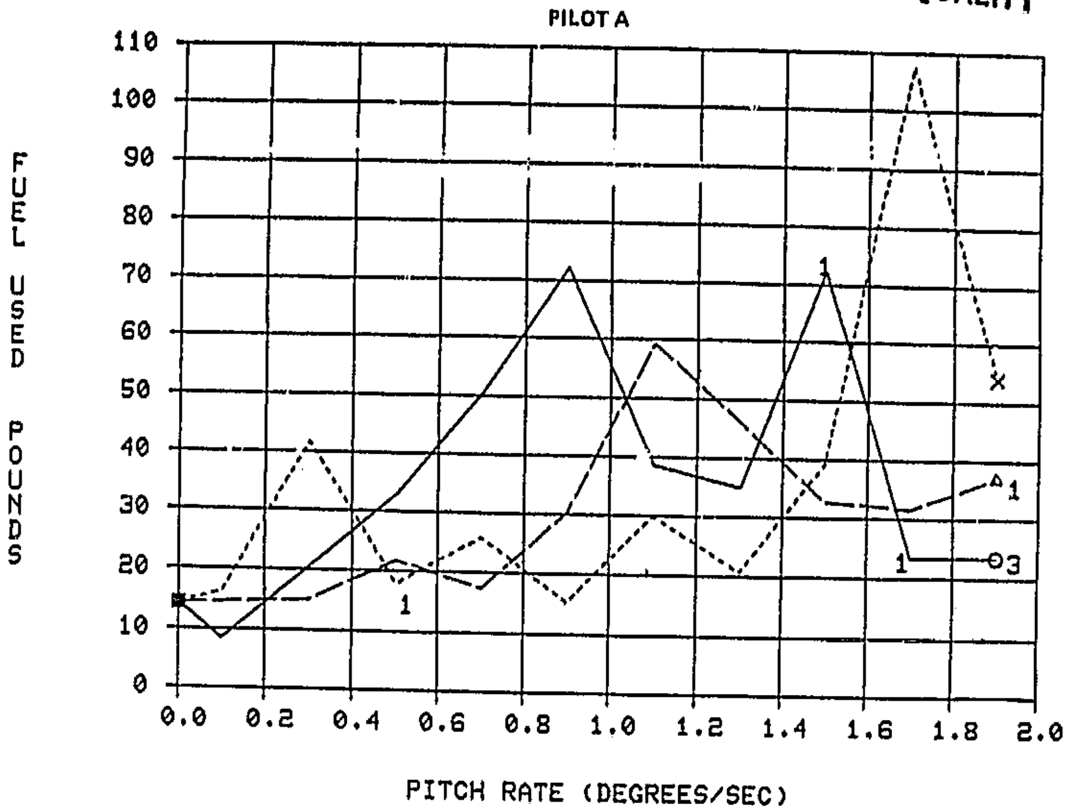

PILOT A
FINAL RSS VELOCITY FT/SEC
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)
1
3

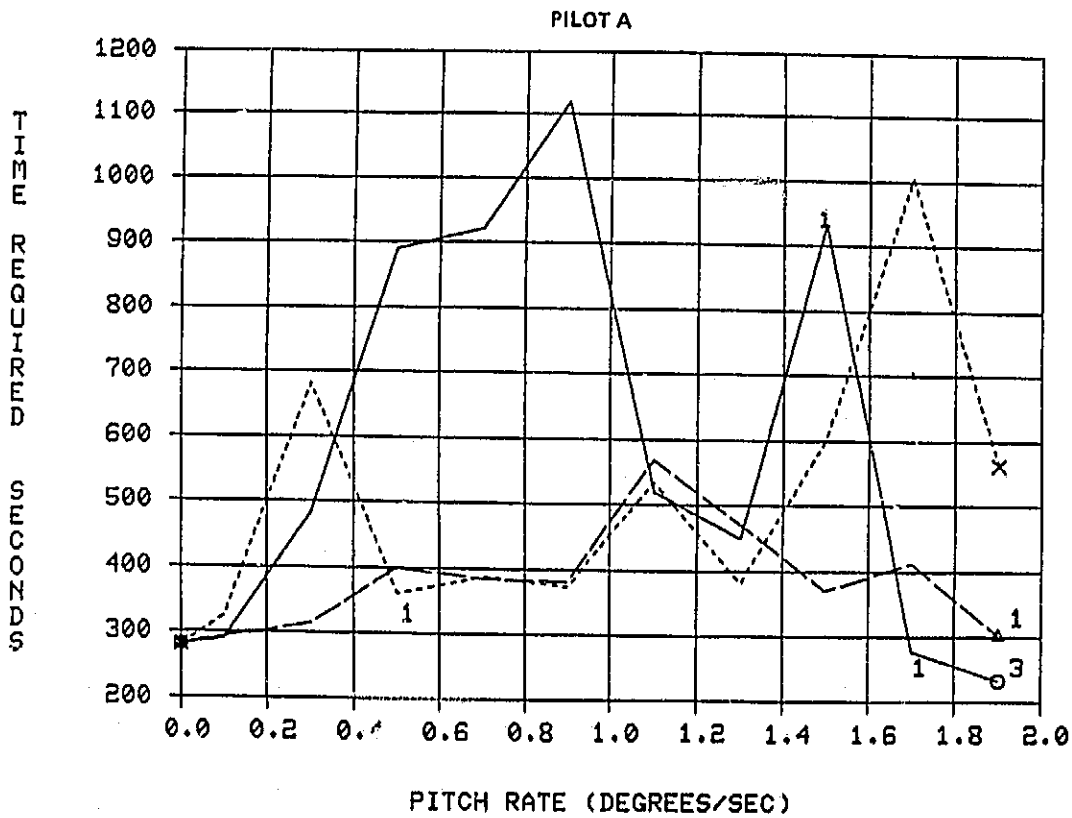
PILOT A

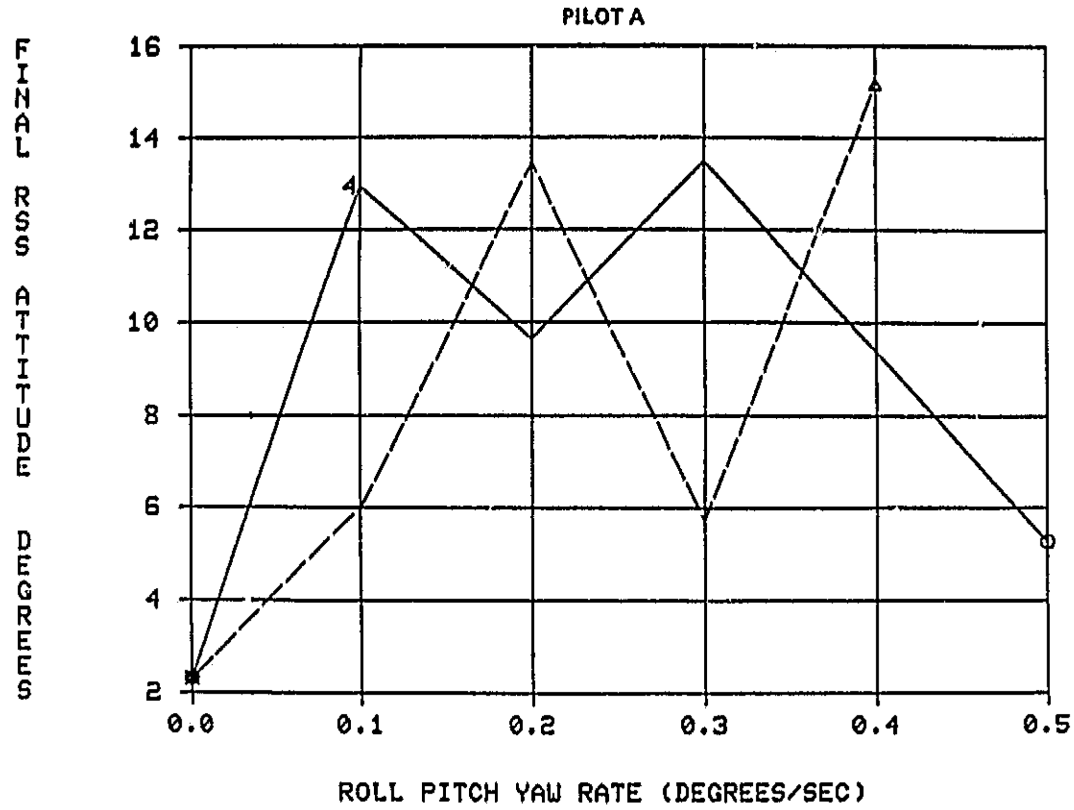


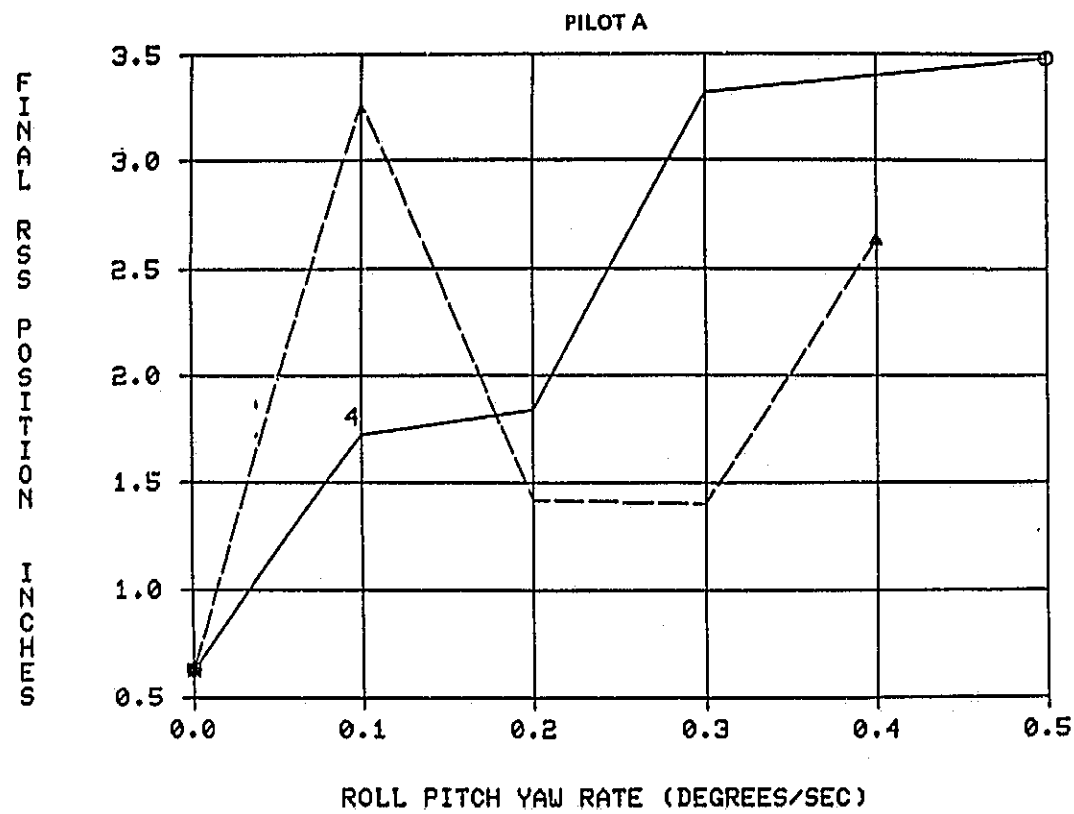
PILOT A

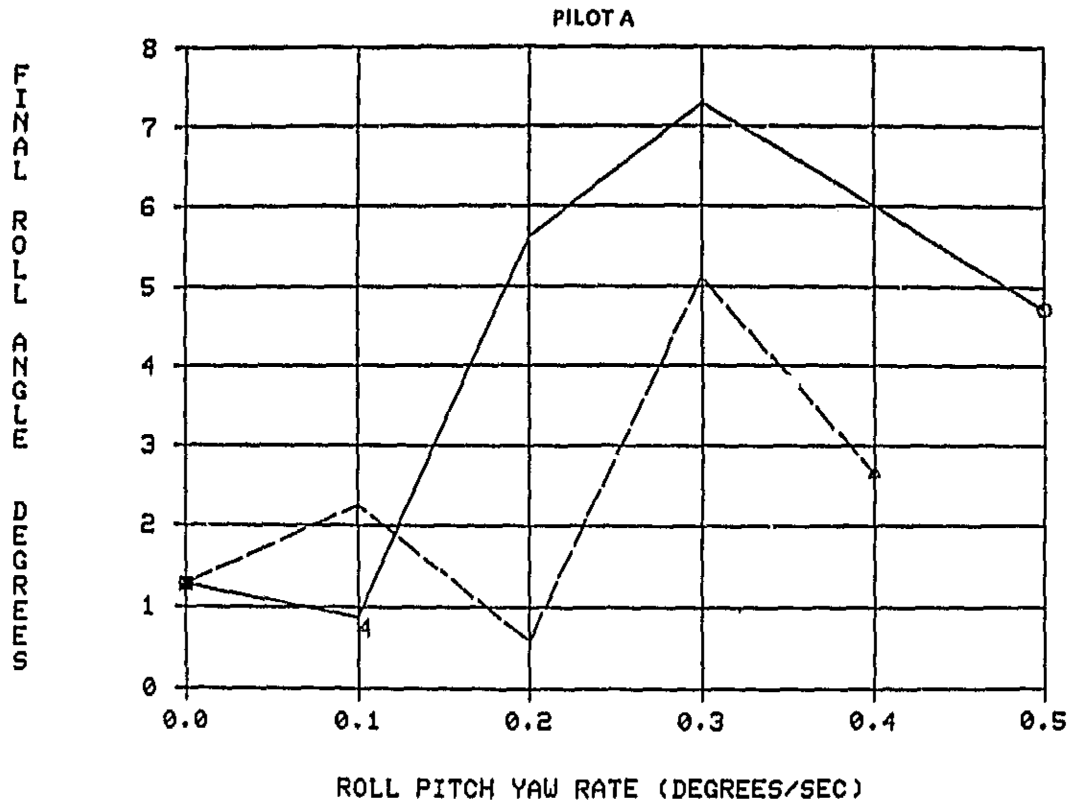


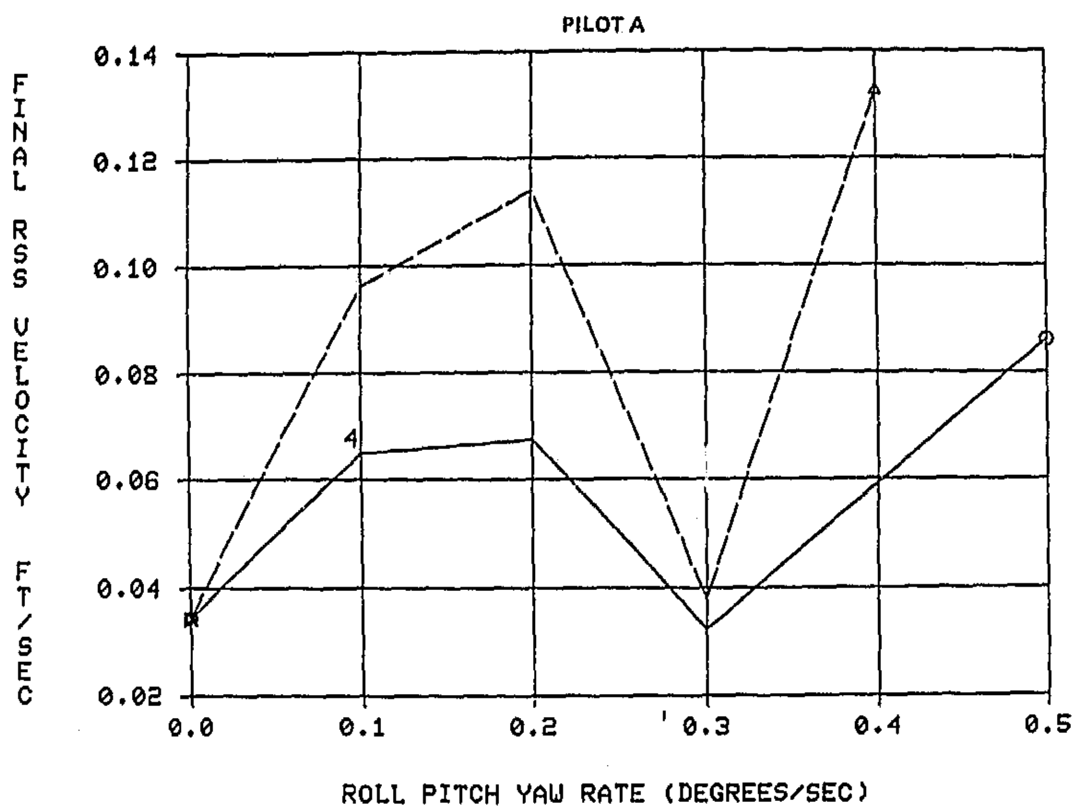

PILOT A
FUEL USED POUNDS
110
100
90
80
70
60
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
1
1
1
1
3
PITCH RATE (DEGREES/SEC)

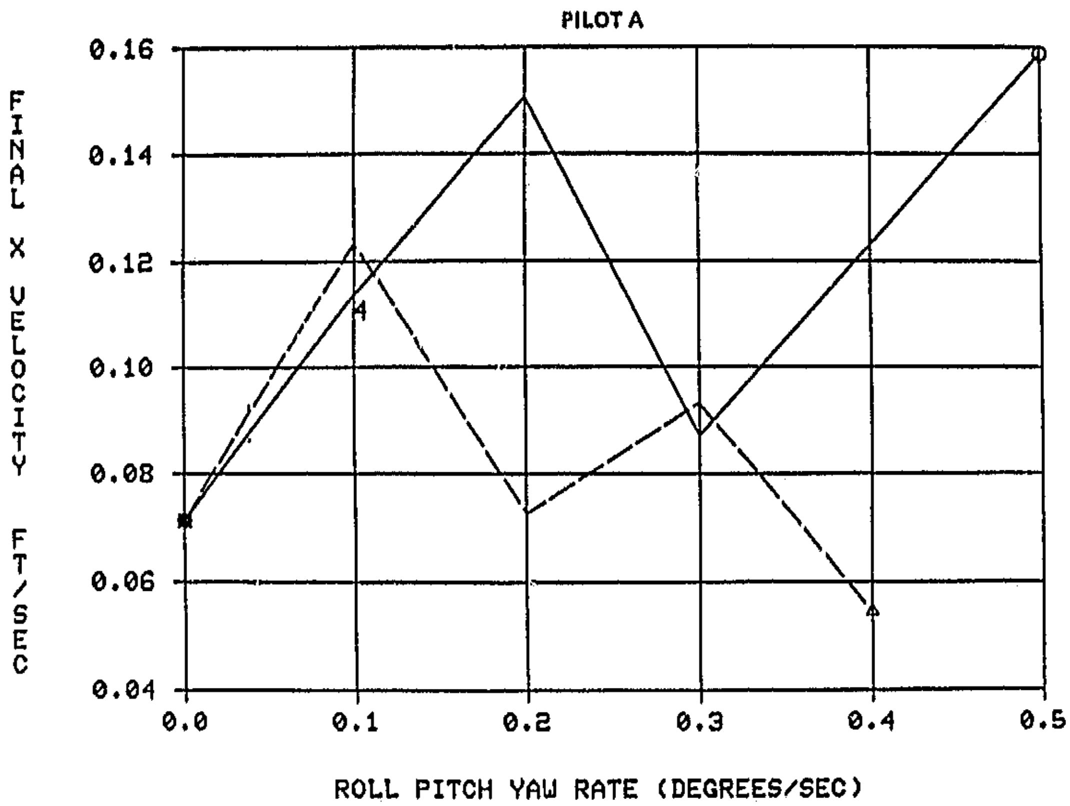

PILOT A
TIME REQUIRED SECONDS
1200
1100
1000
900
800
700
600
500
400
300
200
0.0
0.2
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
1
1
1
1
3
PITCH RATE (DEGREES/SEC)

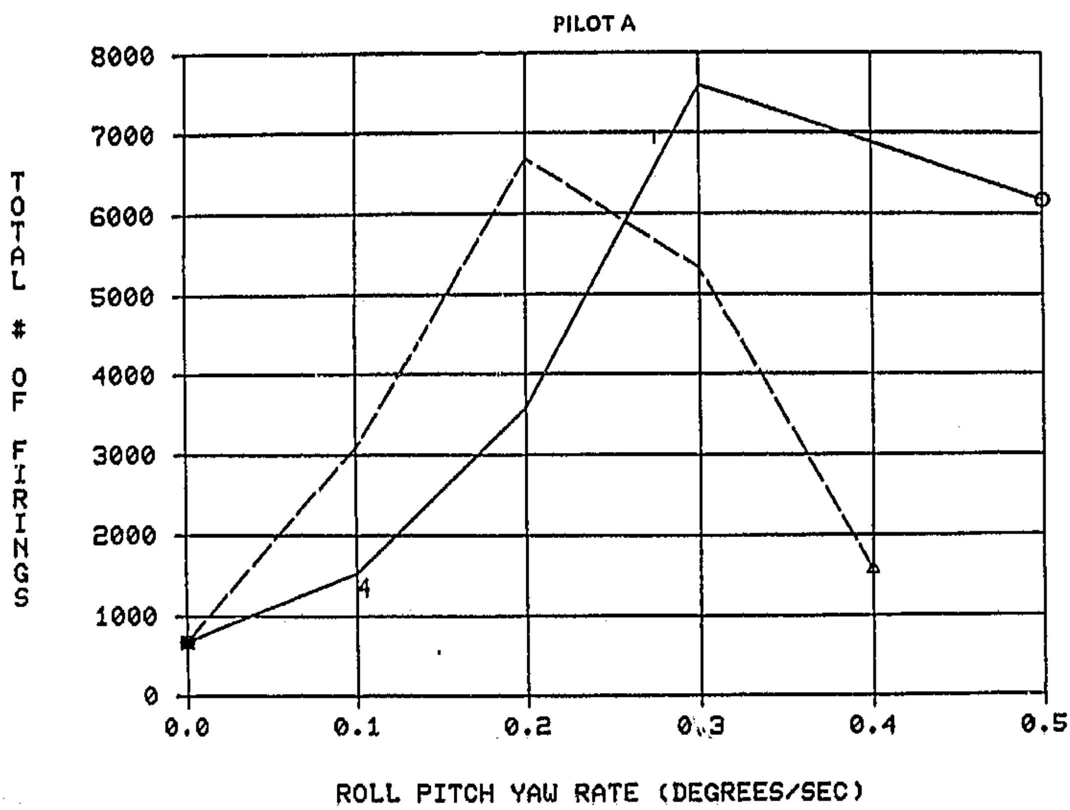

PILOT A
FINAL RSS ATTITUDE DEGREES
16
14
12
10
8
6
4
2
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH YAW RATE (DEGREES/SEC)

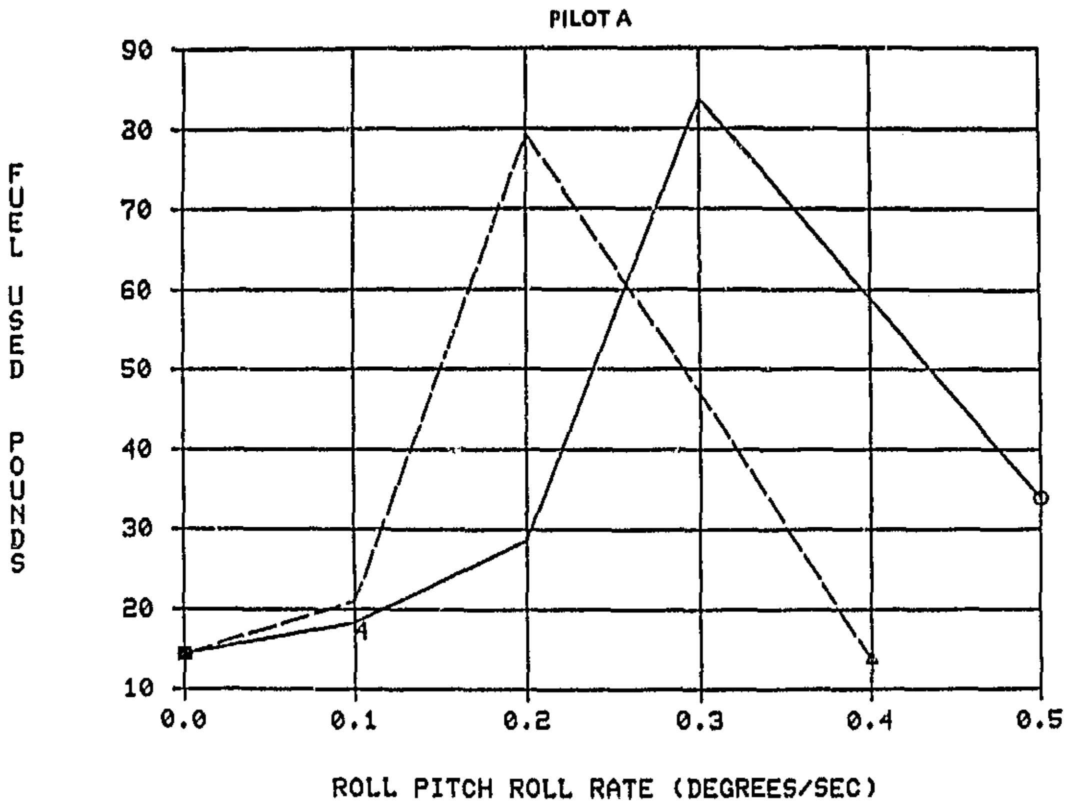

PILOT A
FINAL RSS POSITION INCHES
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH YAW RATE (DEGREES/SEC)

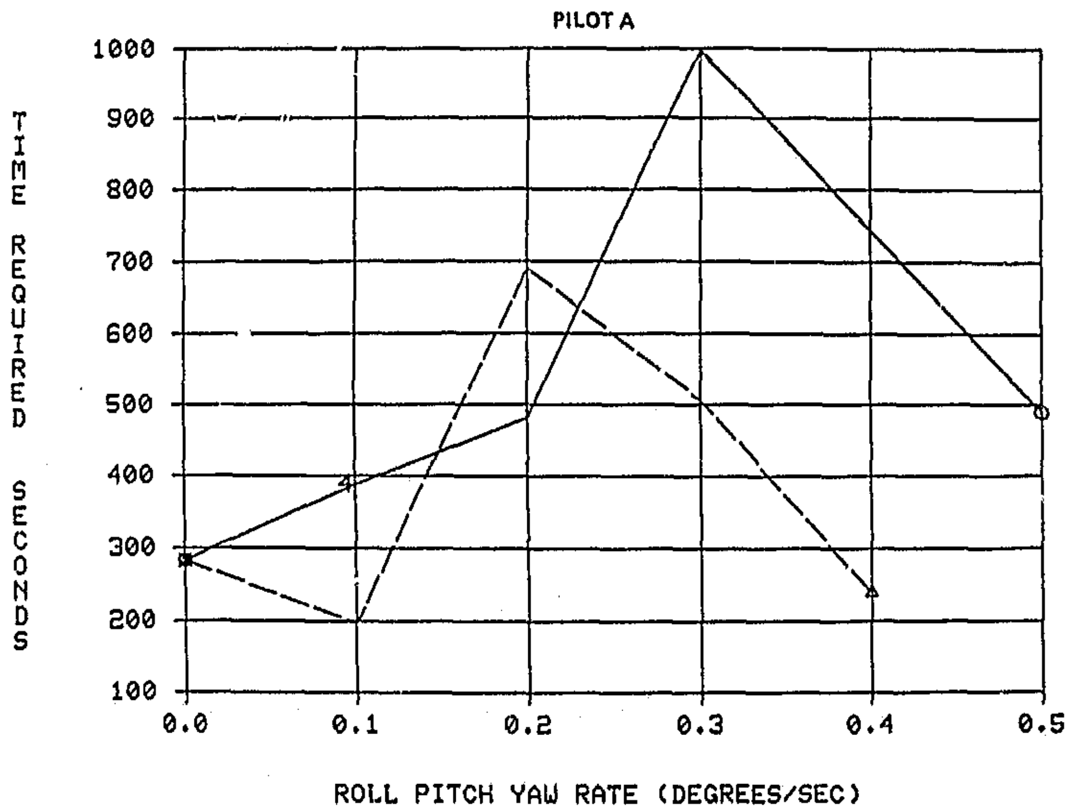

PILOT A
FINAL ROLL ANGLE DEGREES
8
7
6
5
4
3
2
1
0
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH YAW RATE (DEGREES/SEC)

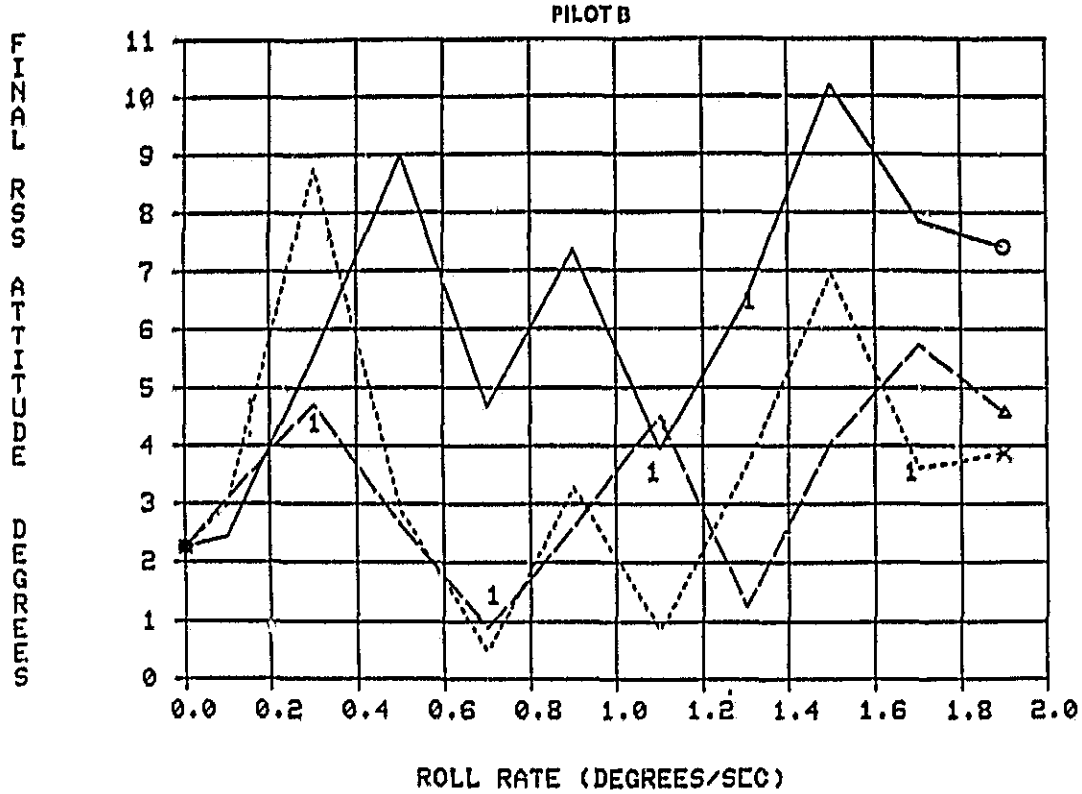

PILOT A
FINAL RSS VELOCITY FT/SEC
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH YAW RATE (DEGREES/SEC)

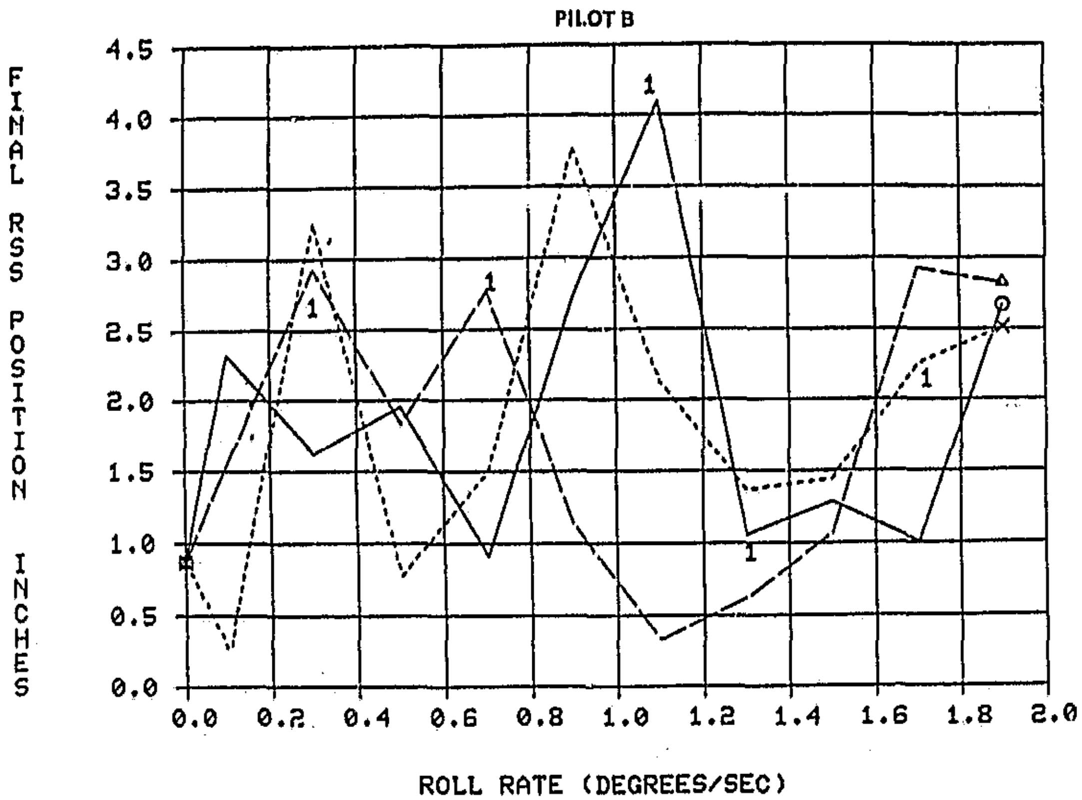

PILOT A
FINAL X VELOCITY FT/SEC
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH YAW RATE (DEGREES/SEC)

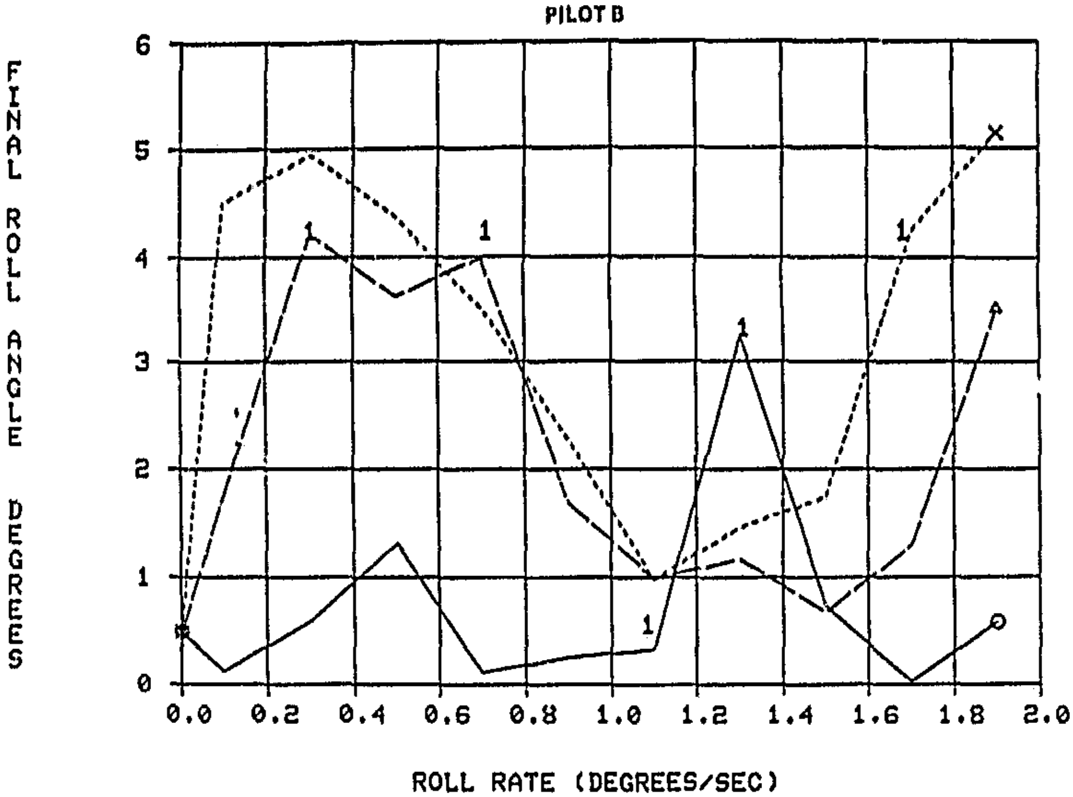

PILOT A
TOTAL # OF FIRINGS
8000
7000
6000
5000
4000
3000
2000
1000
0
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH YAW RATE (DEGREES/SEC)

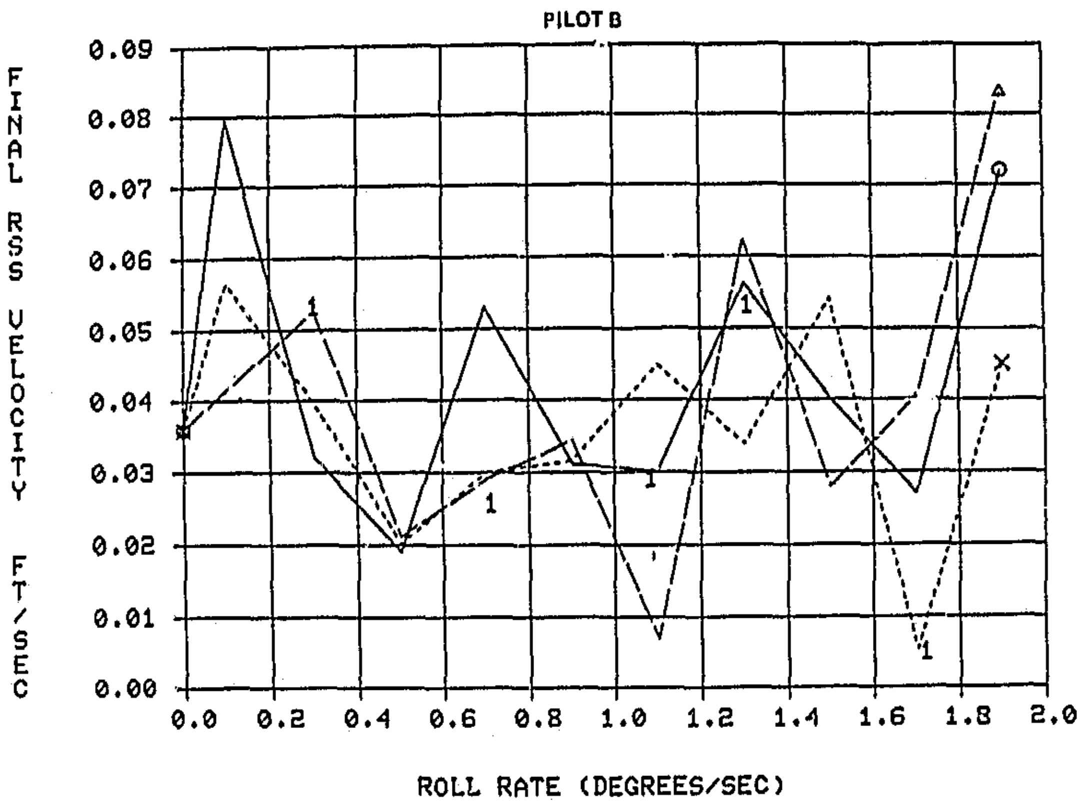

PILOT A
90
80
70
60
50
40
30
20
10
FUEL USED POUNDS
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH ROLL RATE (DEGREES/SEC)

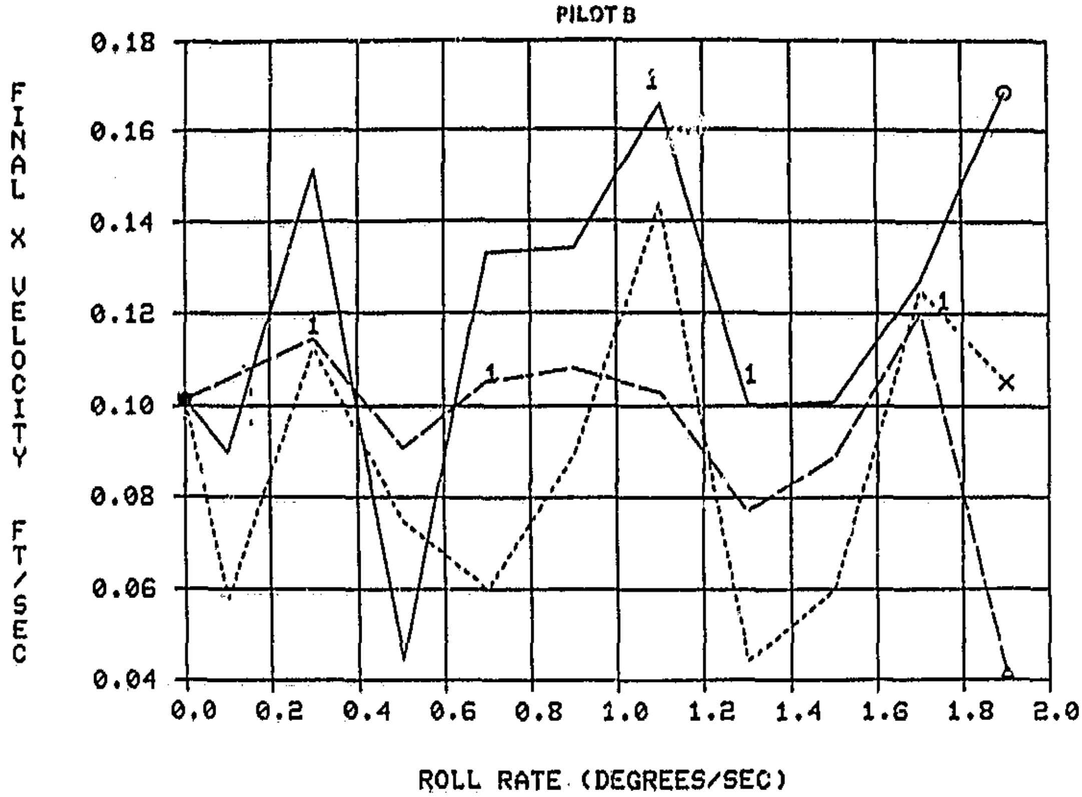

PILOT A
1000
900
800
700
600
500
400
300
200
100
TIME REQUIRED SECONDS
0.0
0.1
0.2
0.3
0.4
0.5
ROLL PITCH YAW RATE (DEGREES/SEC)

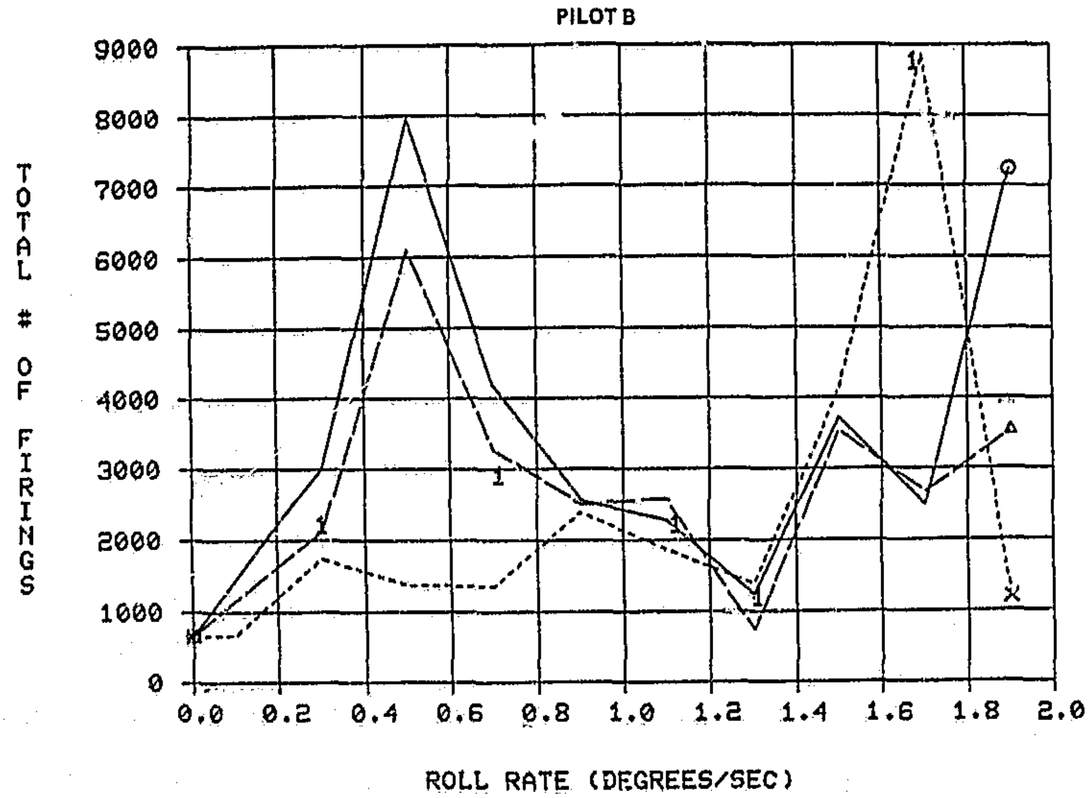

PILOT B
FINAL RSS ATTITUDE DEGREES
11
10
9
8
7
6
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

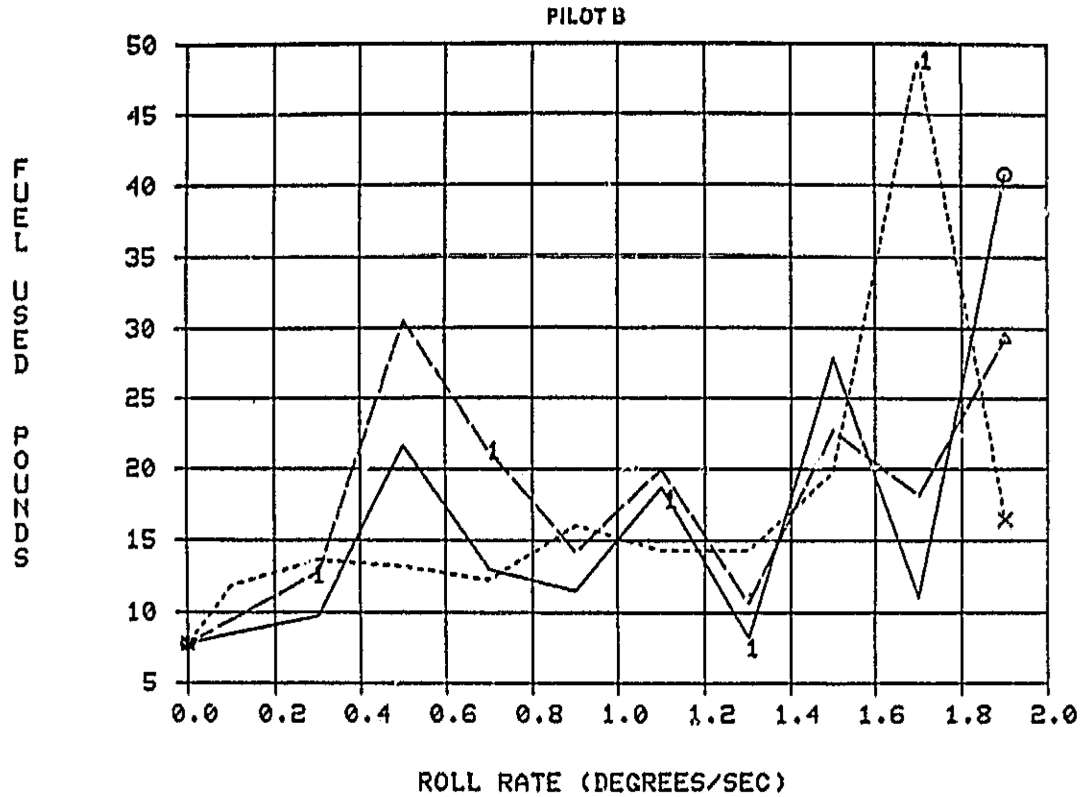

PILOT B
FINAL RSS POSITION INCHES
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

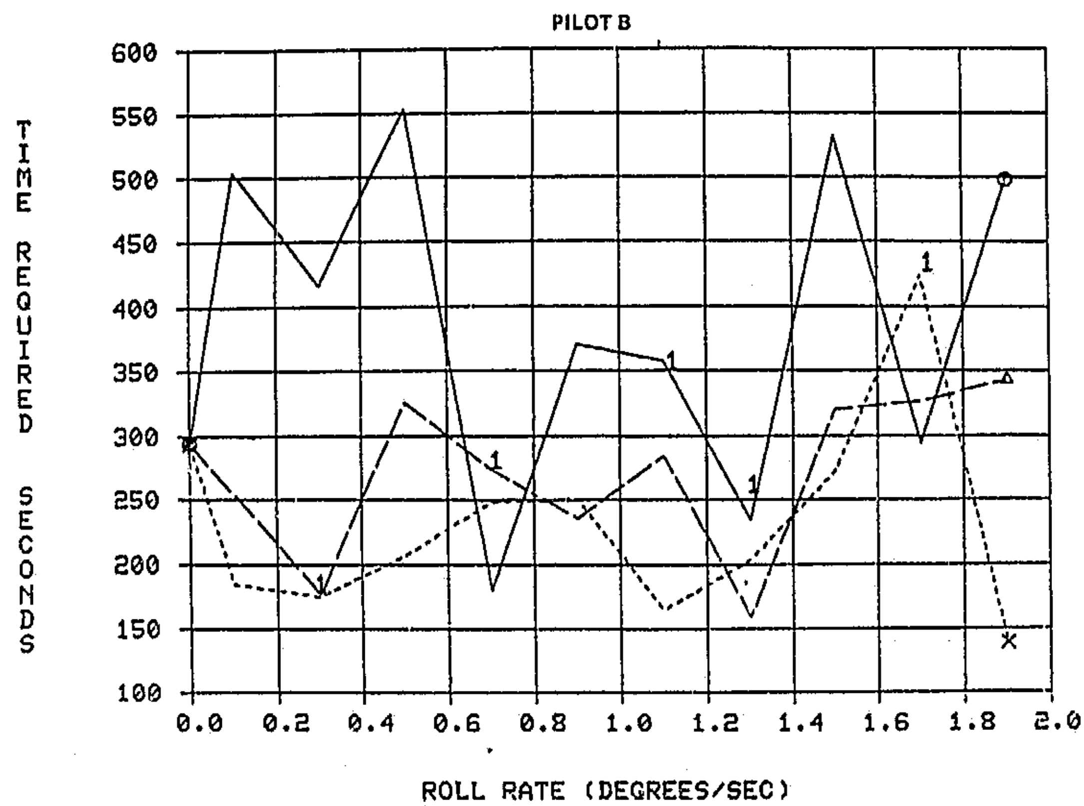

PILOT B
FINAL ROLL ANGLE DEGREES
0
1
2
3
4
5
6
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

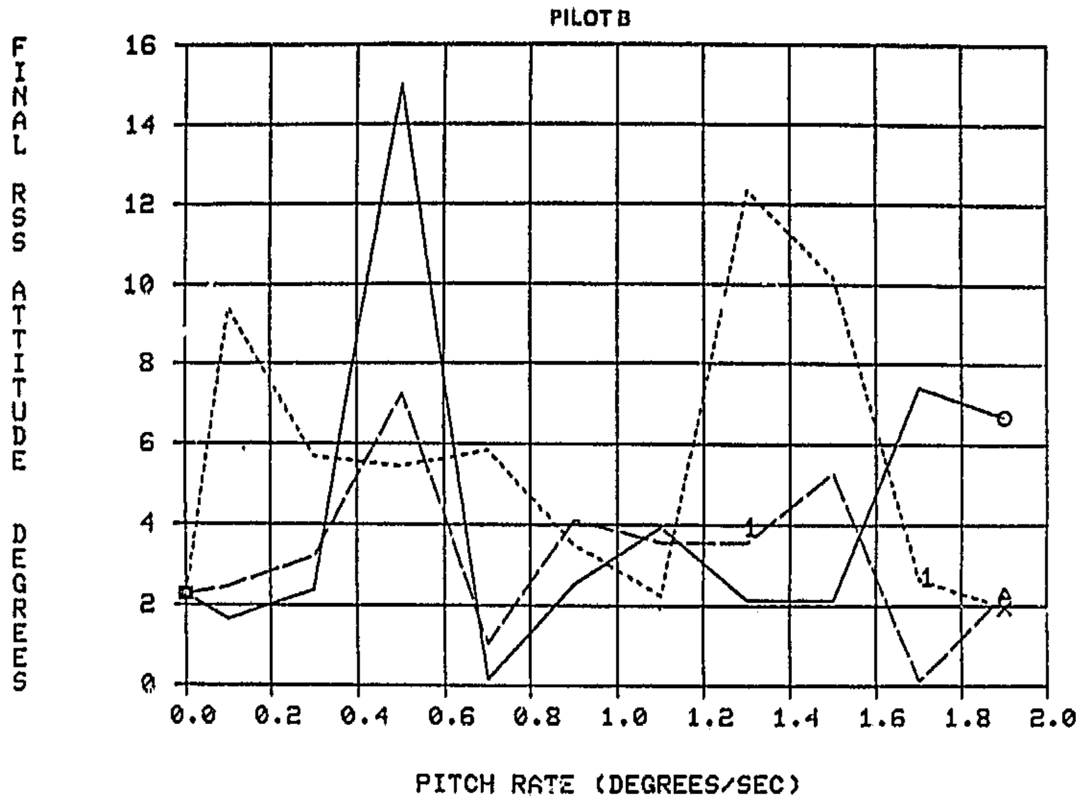

PILOT B
FINAL RSS VELOCITY FT/SEC
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

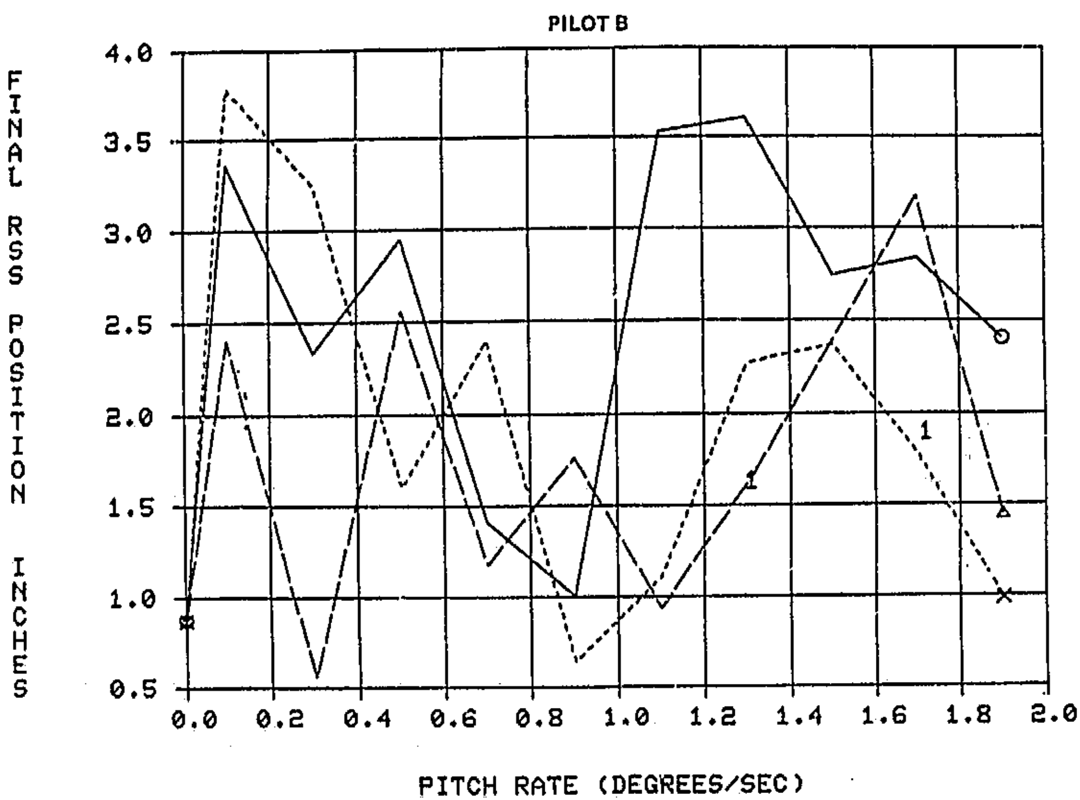

PILOT B
FINAL X VELOCITY FT/SEC
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)

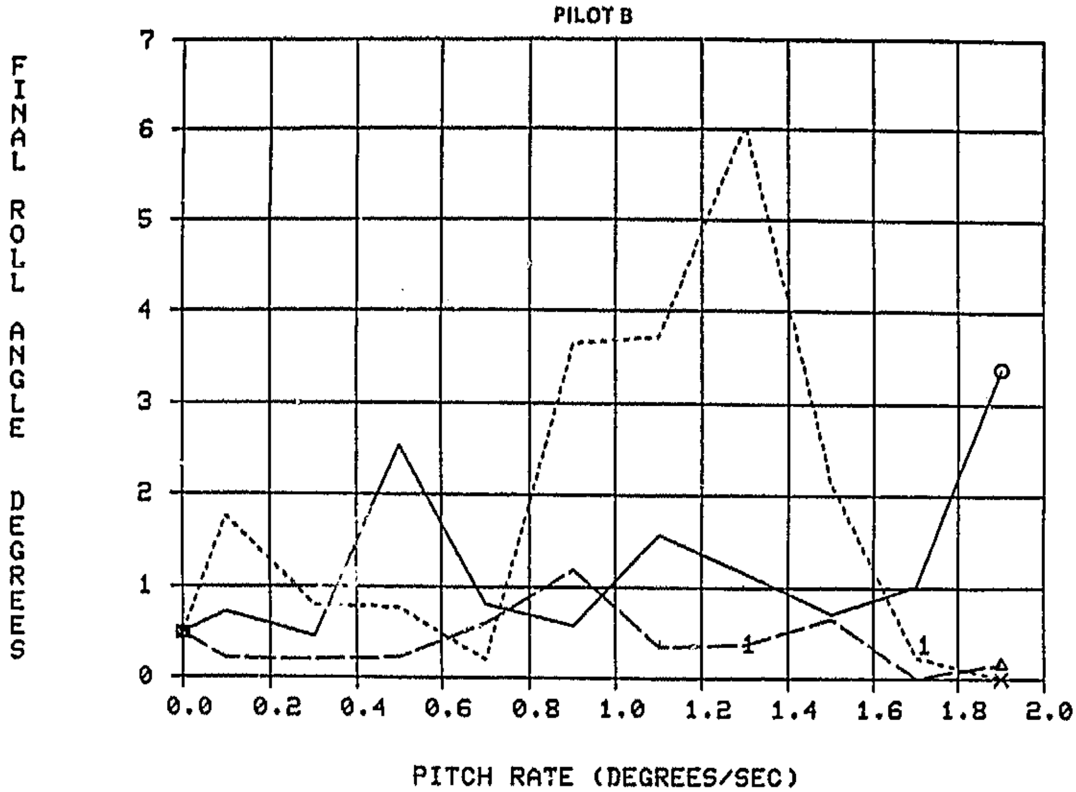

PILOT B
TOTAL # OF FIRINGS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)

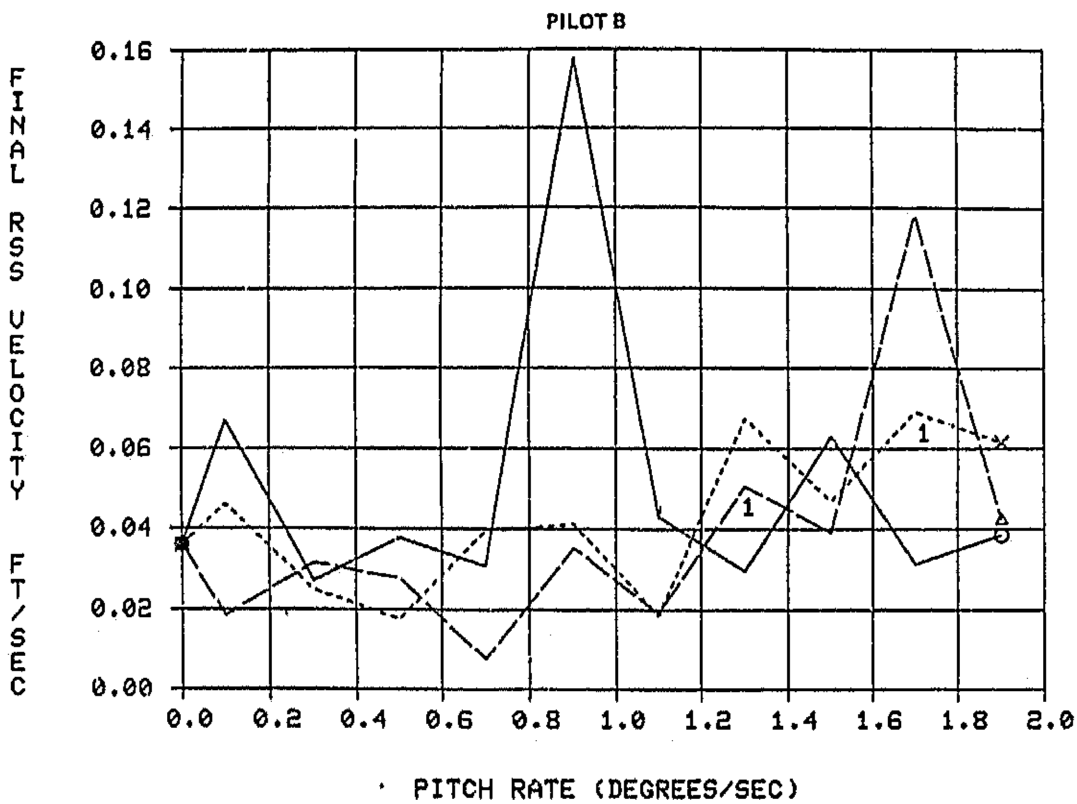

PILOT B
FUEL USED POUNDS
50
45
40
35
30
25
20
15
10
5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

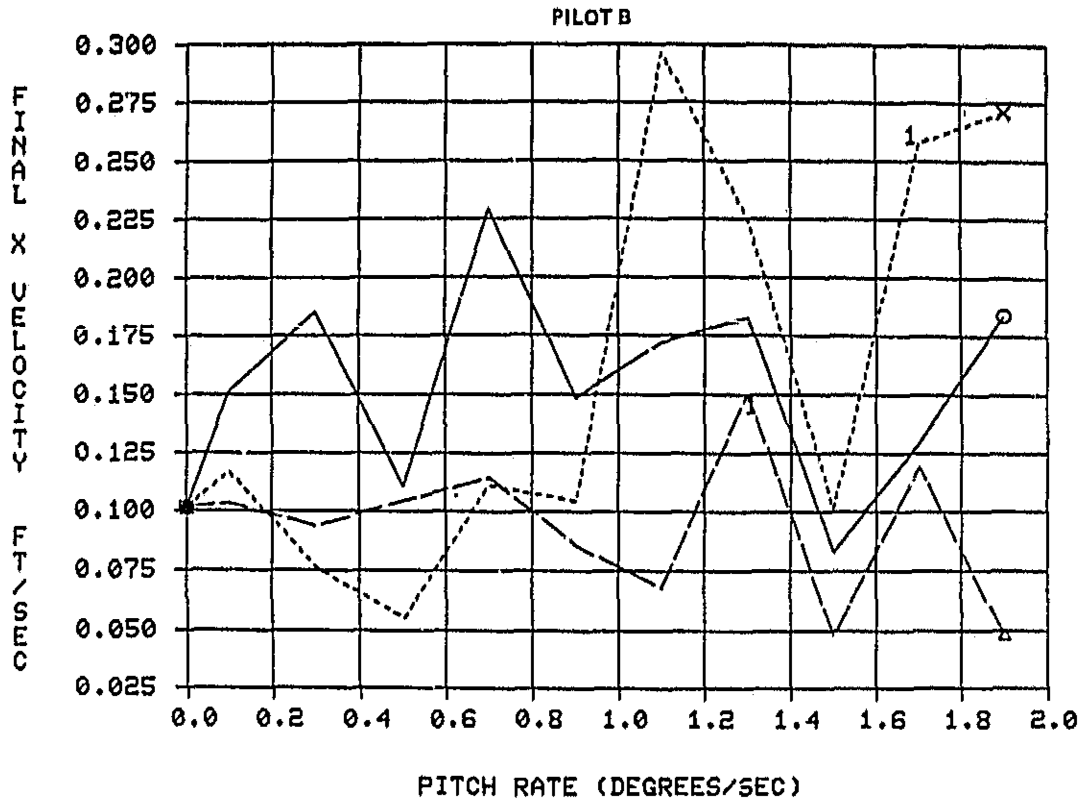

PILOT B
TIME REQUIRED SECONDS
600
550
500
450
400
350
300
250
200
150
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

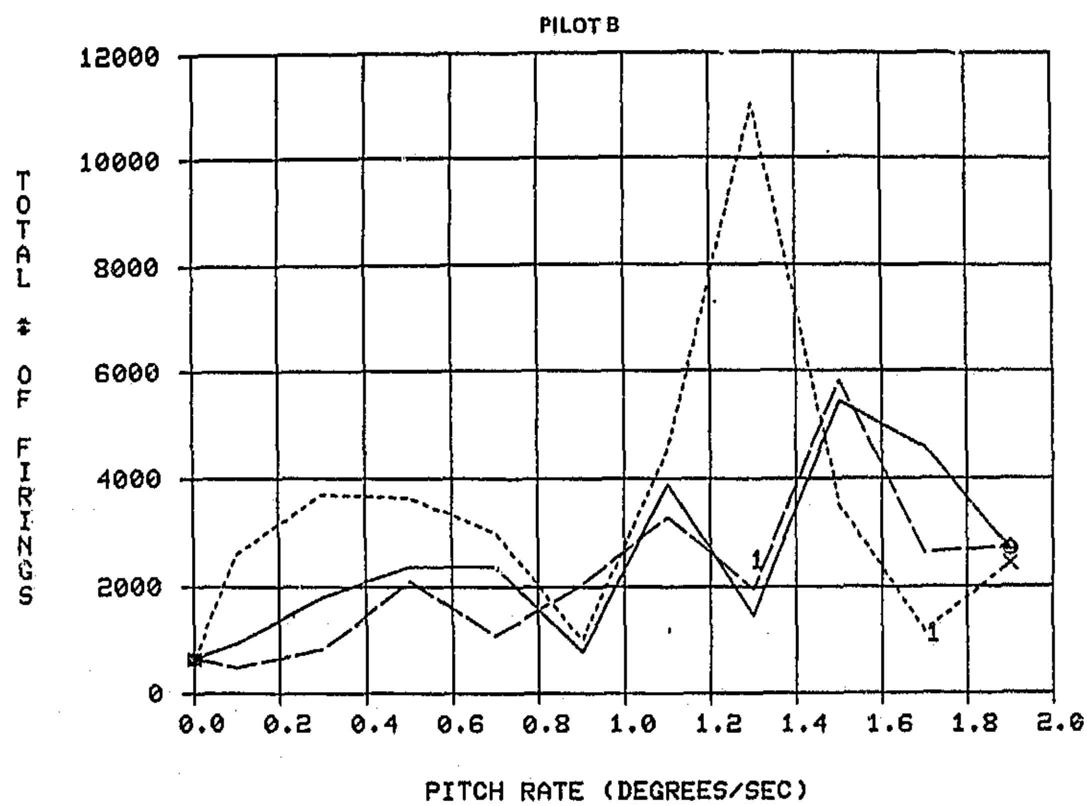

PILOT B
FINAL RSS ATTITUDE DEGREES
16
14
12
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)


PILOT B
FINAL RSS POSITION INCHES
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)

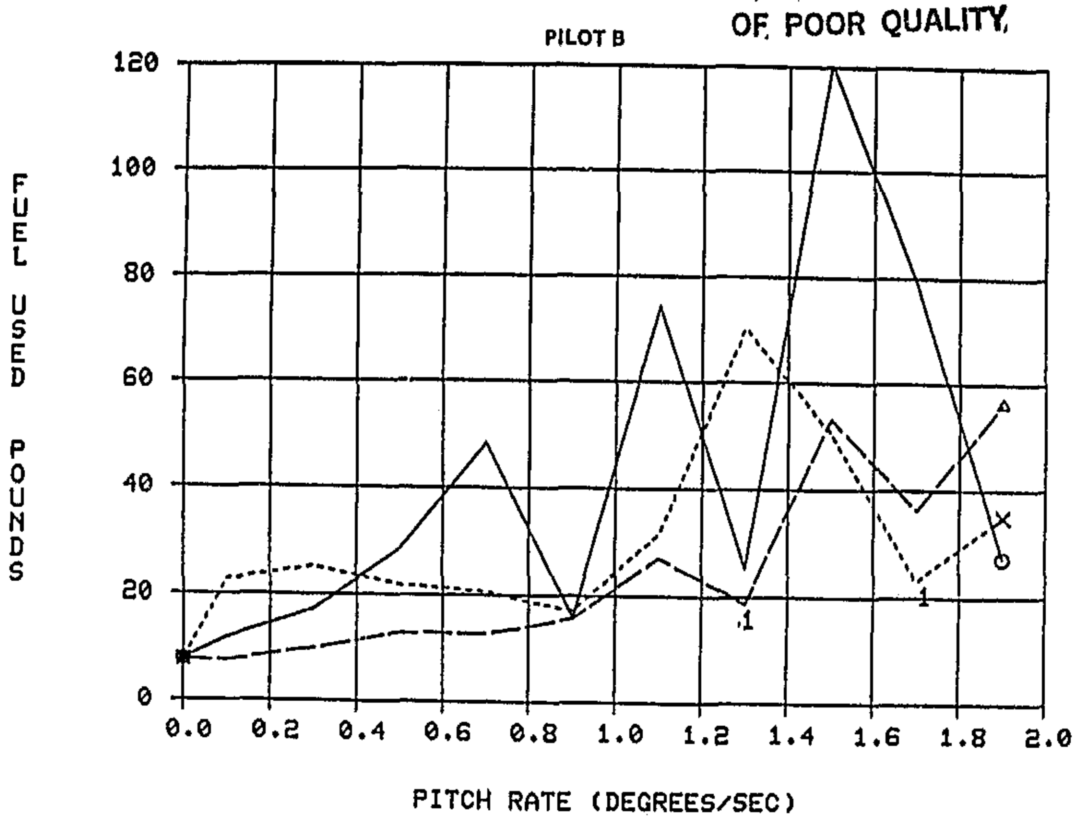

PILOT B
FINAL ROLL ANGLE DEGREES
7
6
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)

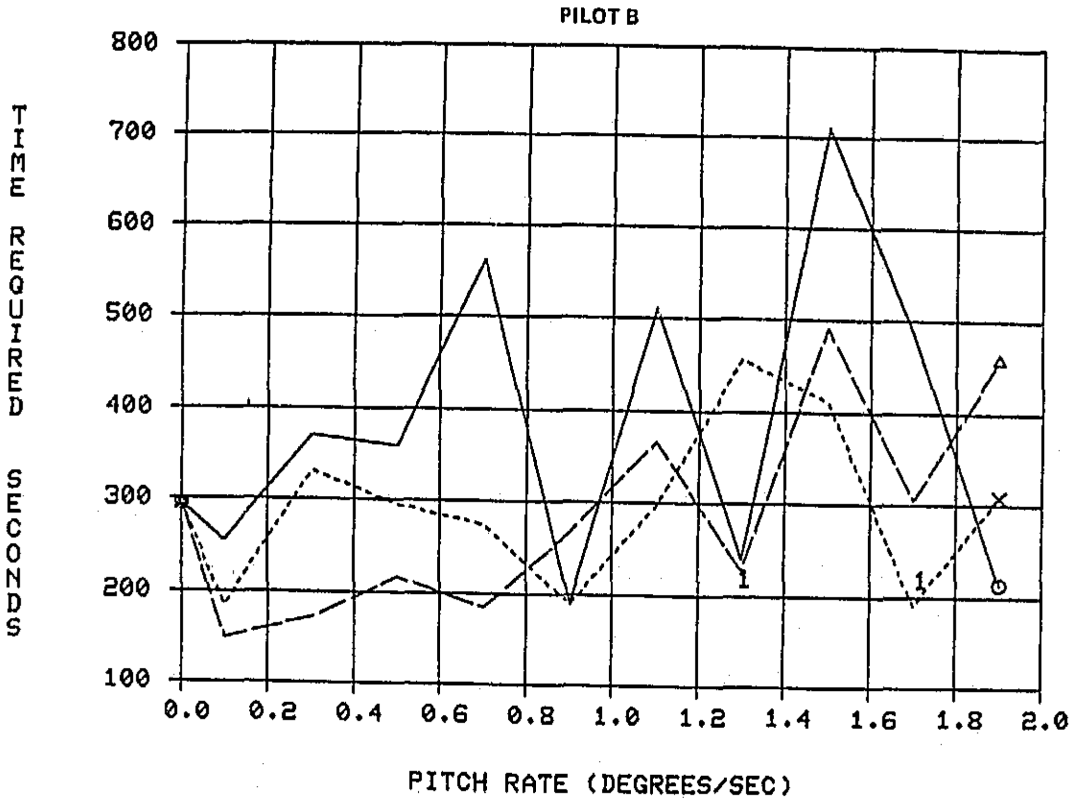

PILOT B
FINAL RSS VELOCITY FT/SEC
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)

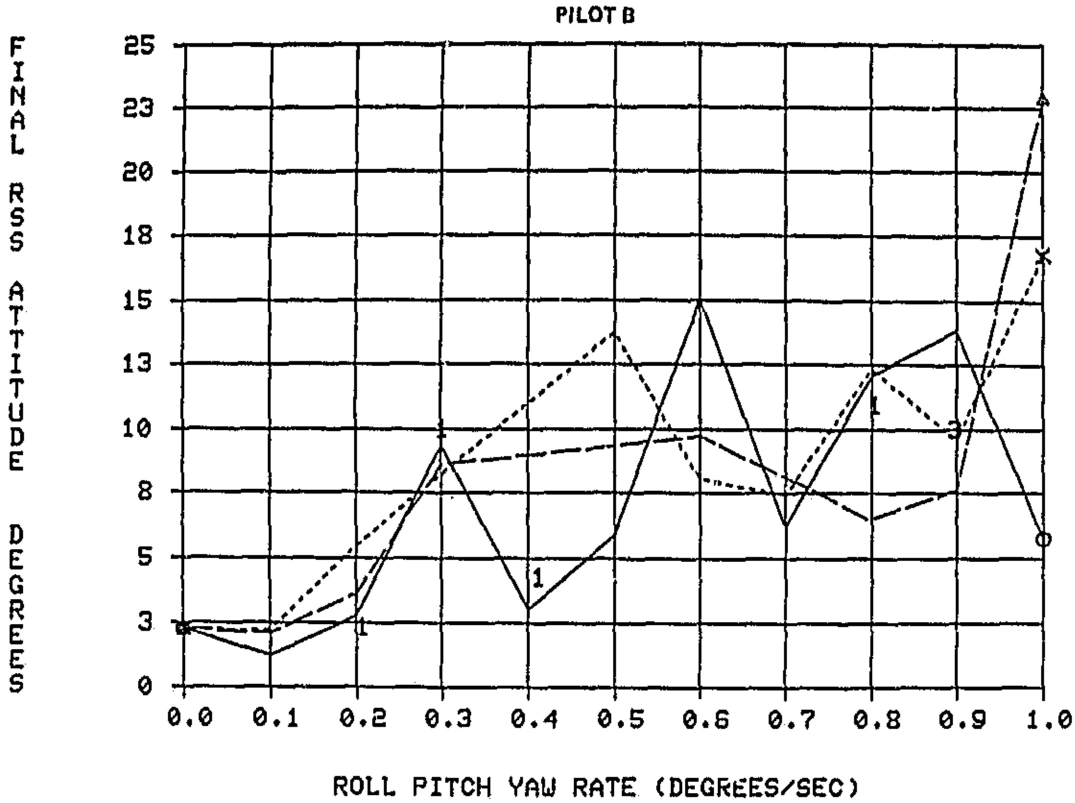

PILOT B
FINAL X VELOCITY FT/SEC
0.300
0.275
0.250
0.225
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

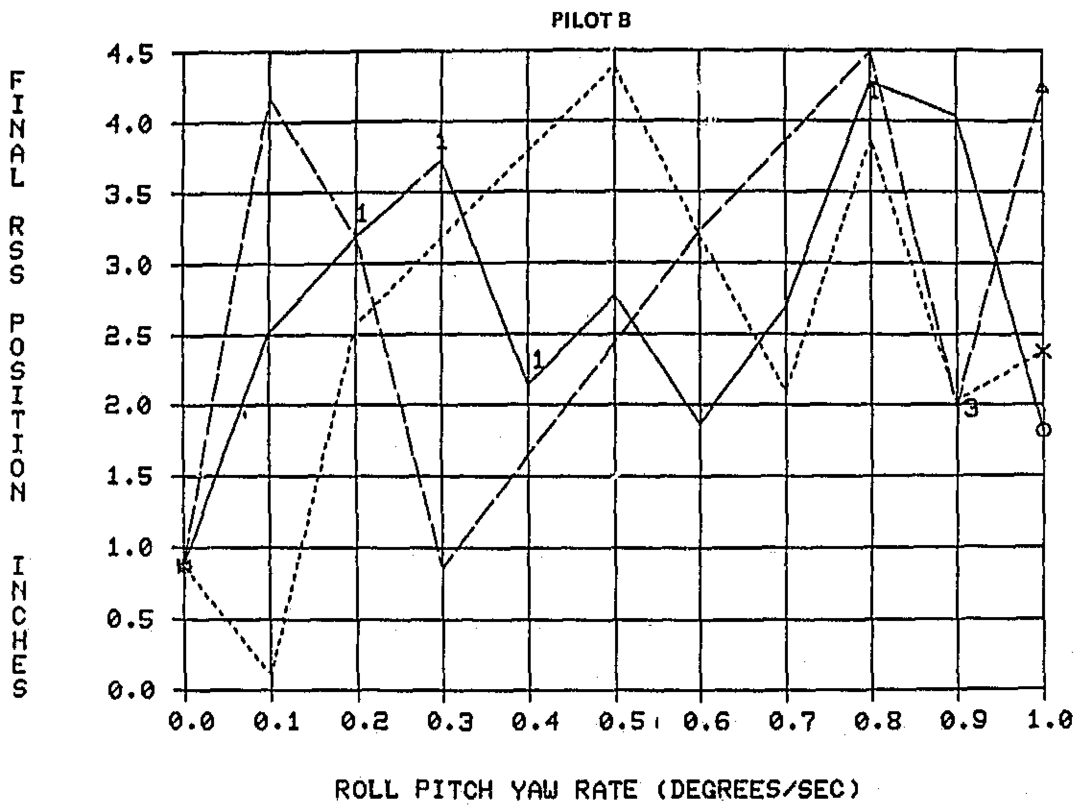

PILOT B
TOTAL # OF FIRINGS
12000
10000
8000
6000
4000
2000
0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

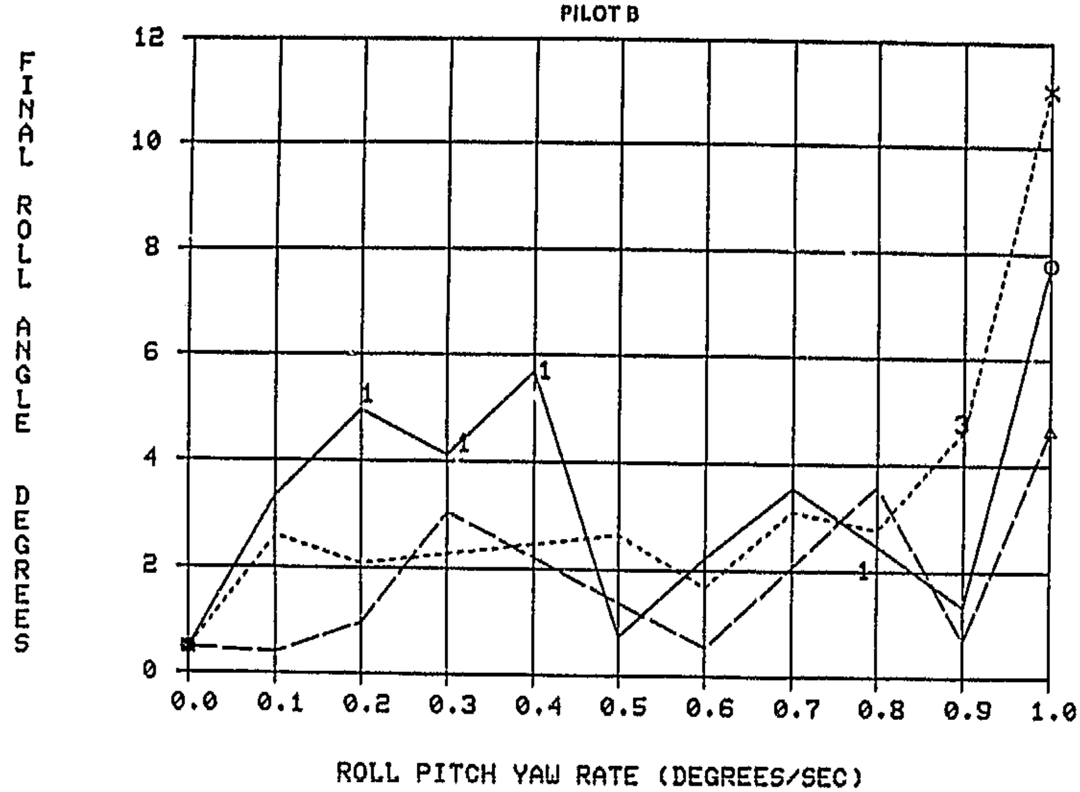
ORIGINAL PAGE IS
OF POOR QUALITY

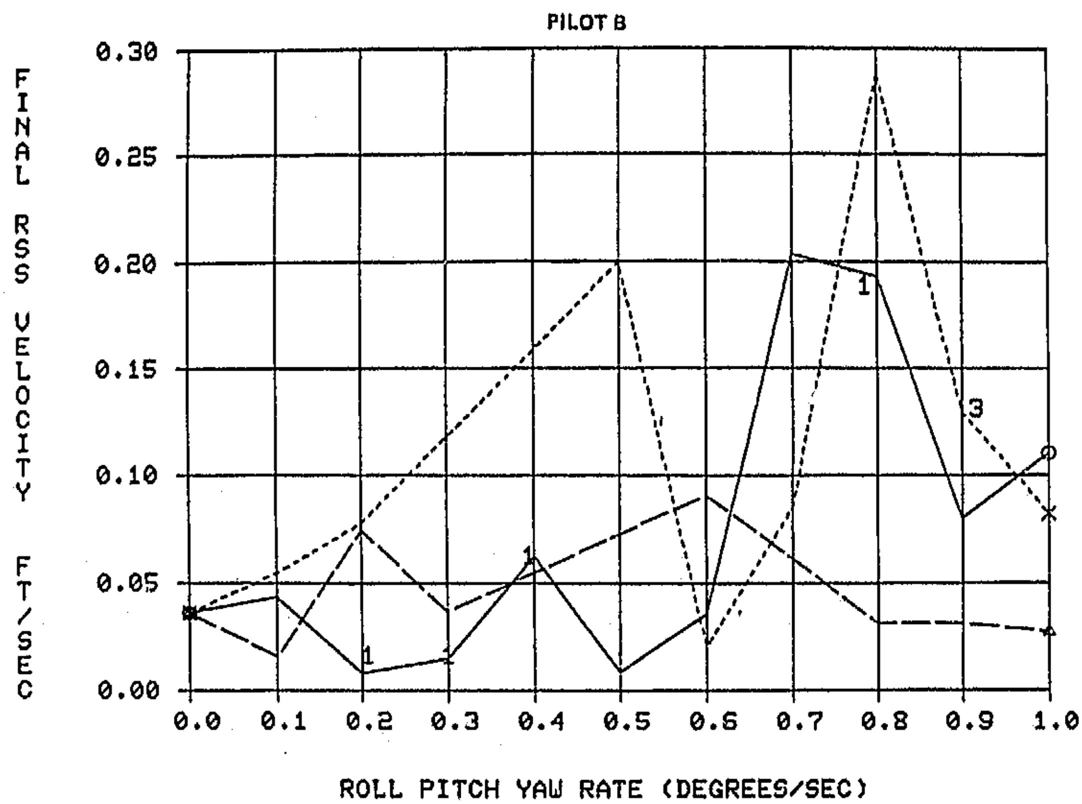


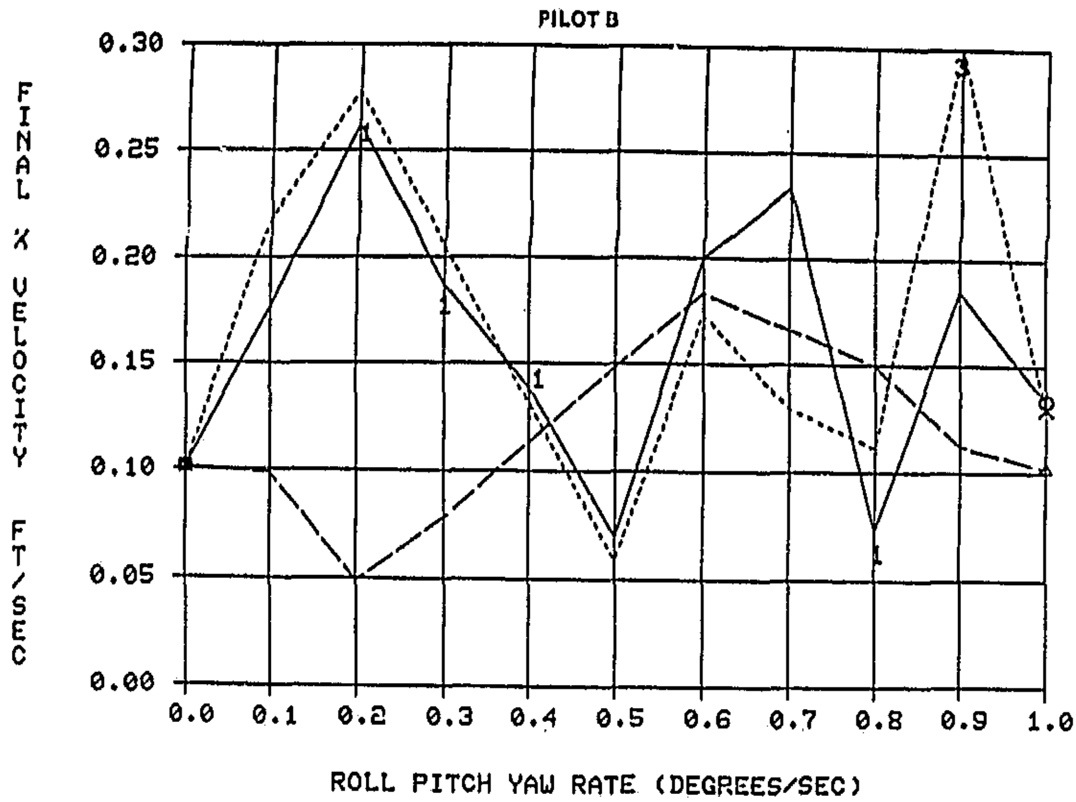


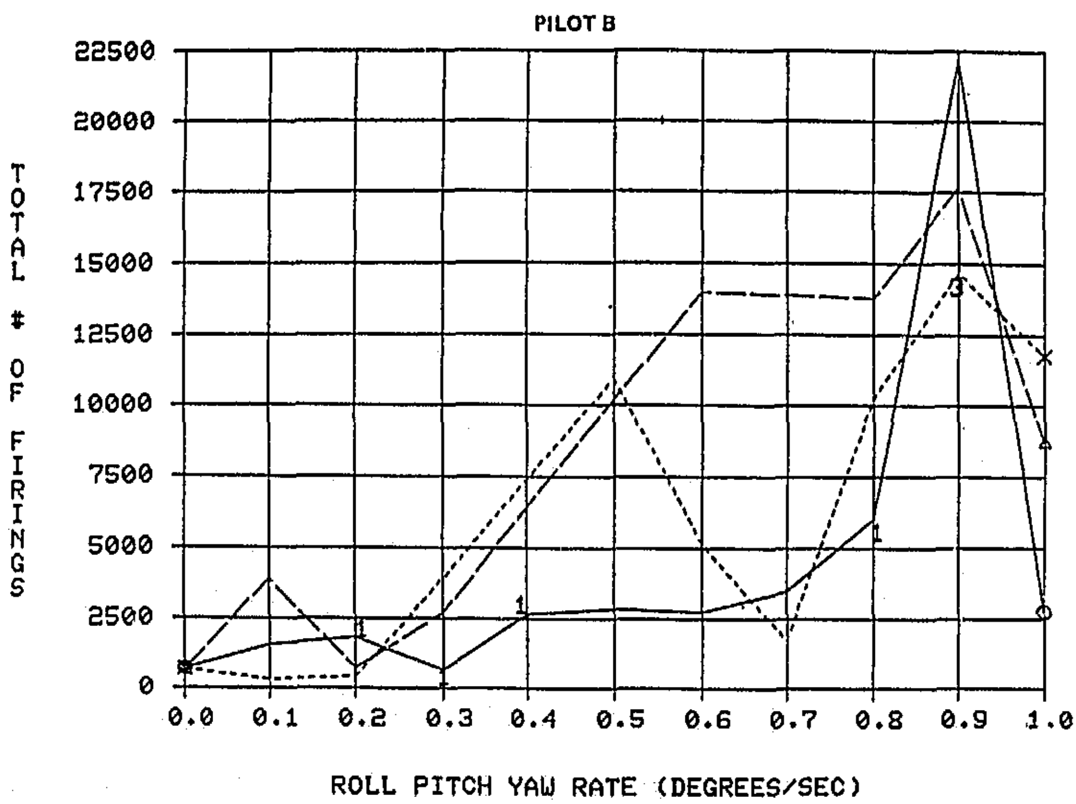

PILOT B
FINAL RSS ATTITUDE DEGREES
25
23
20
18
15
13
10
8
5
3
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

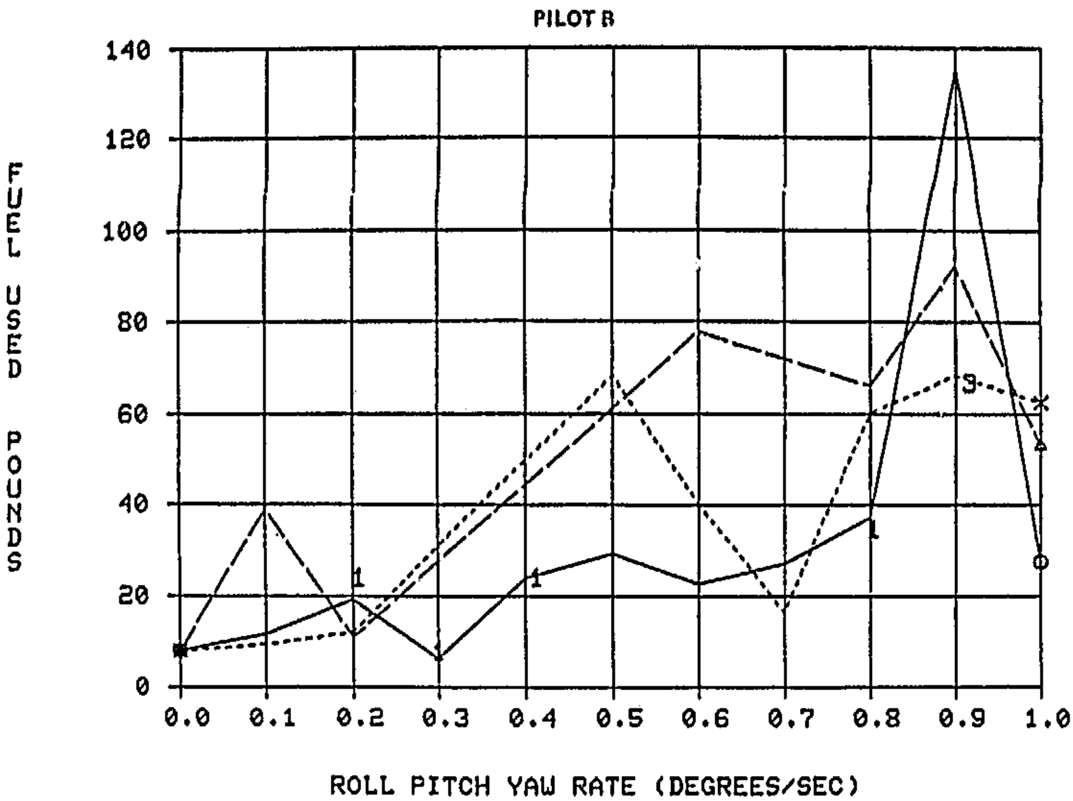

PILOT B
FINAL RSS POSITION INCHES
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

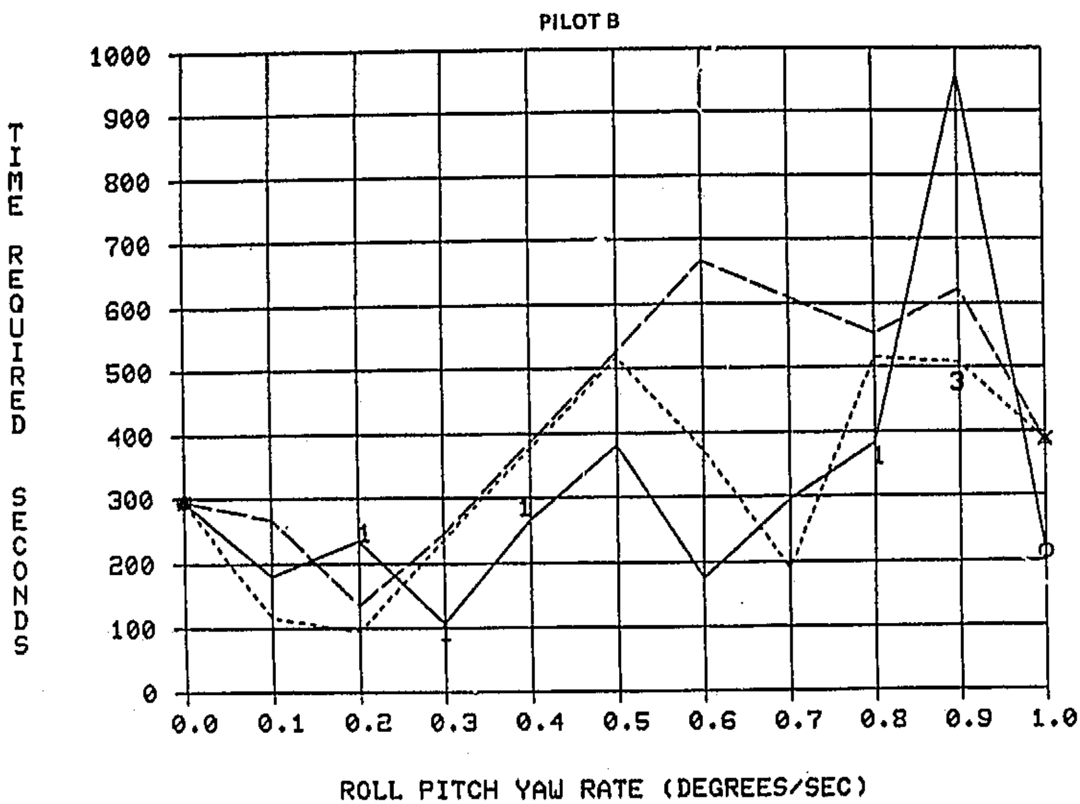

PILOT B
FINAL ROLL ANGLE DEGREES
12
10
8
6
4
2
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

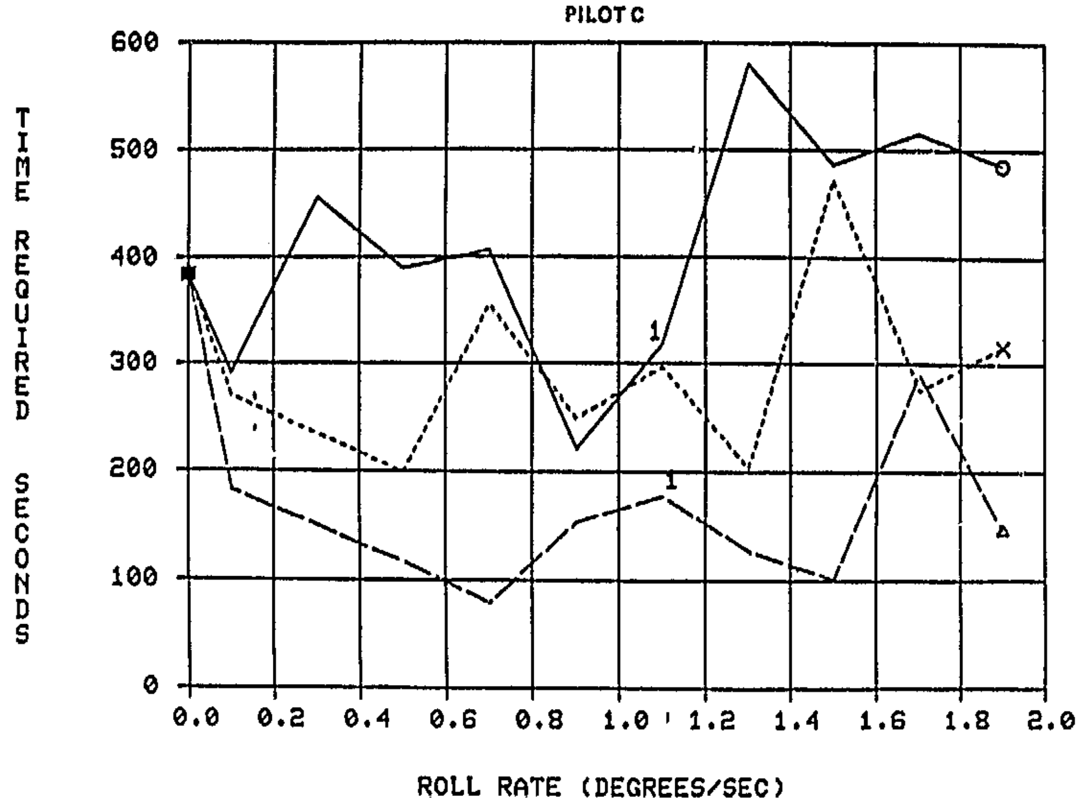

PILOT B
FINAL RSS VELOCITY FT/SEC
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

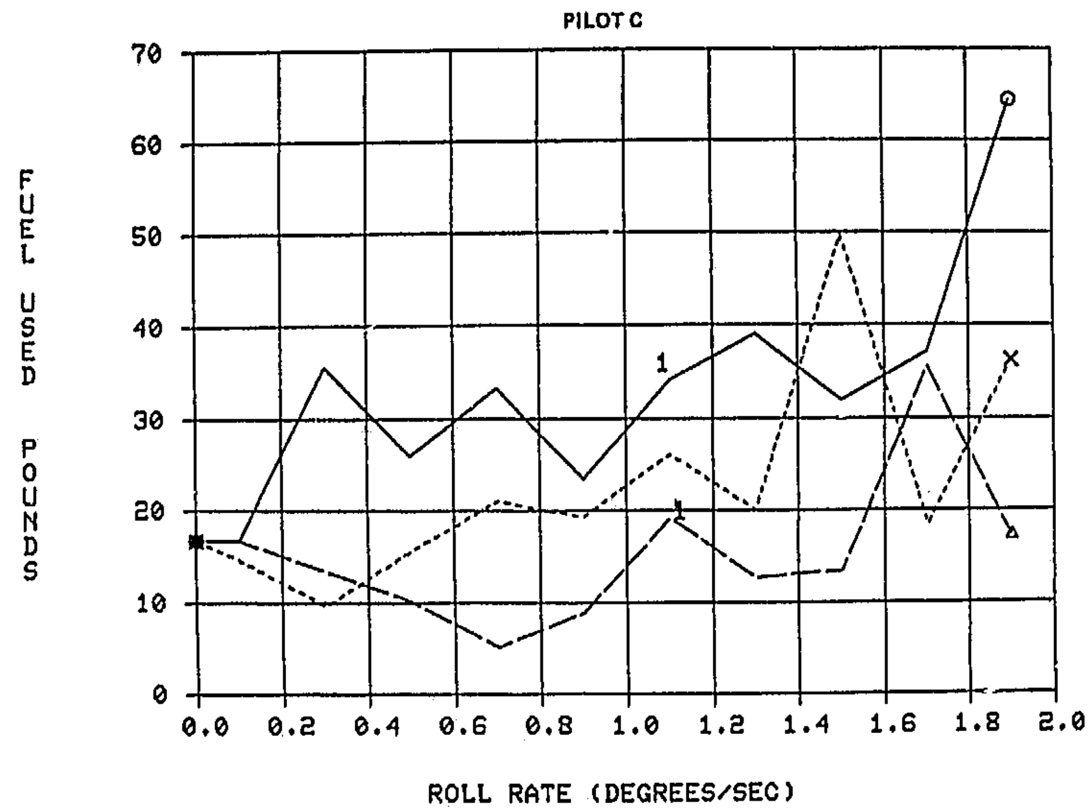

PILOT B
FINAL X VELOCITY FT/SEC
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

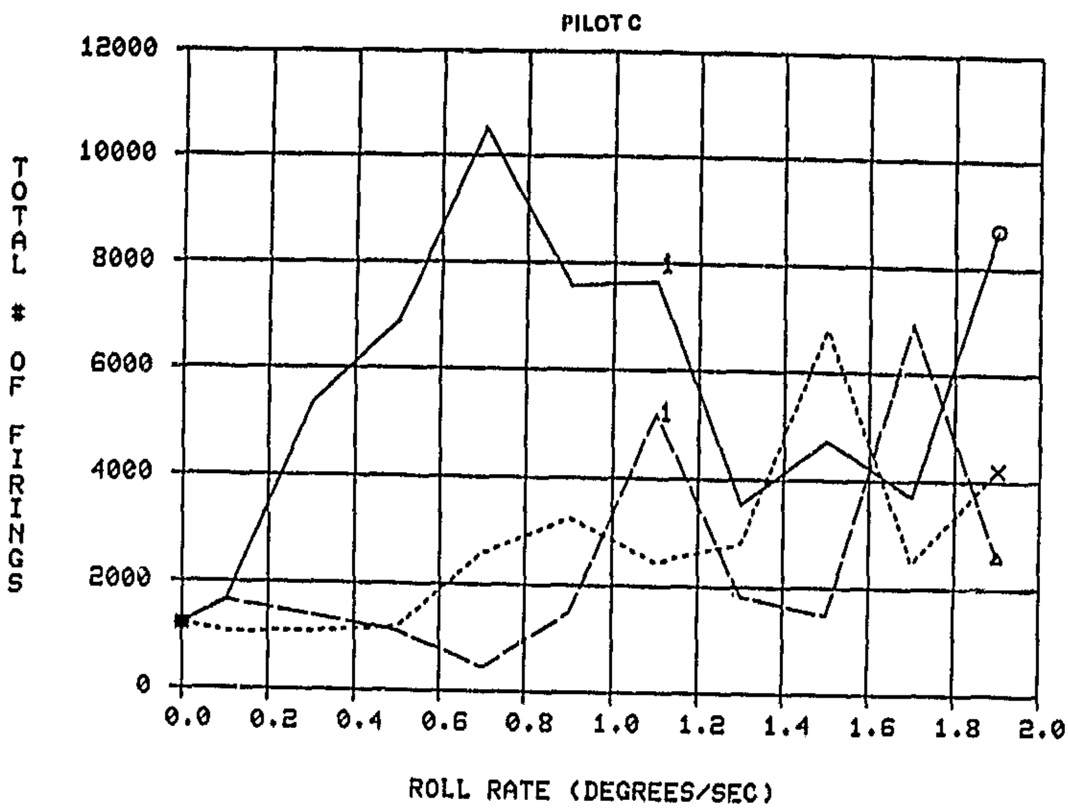

PILOT B
TOTAL # OF FIRINGS
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

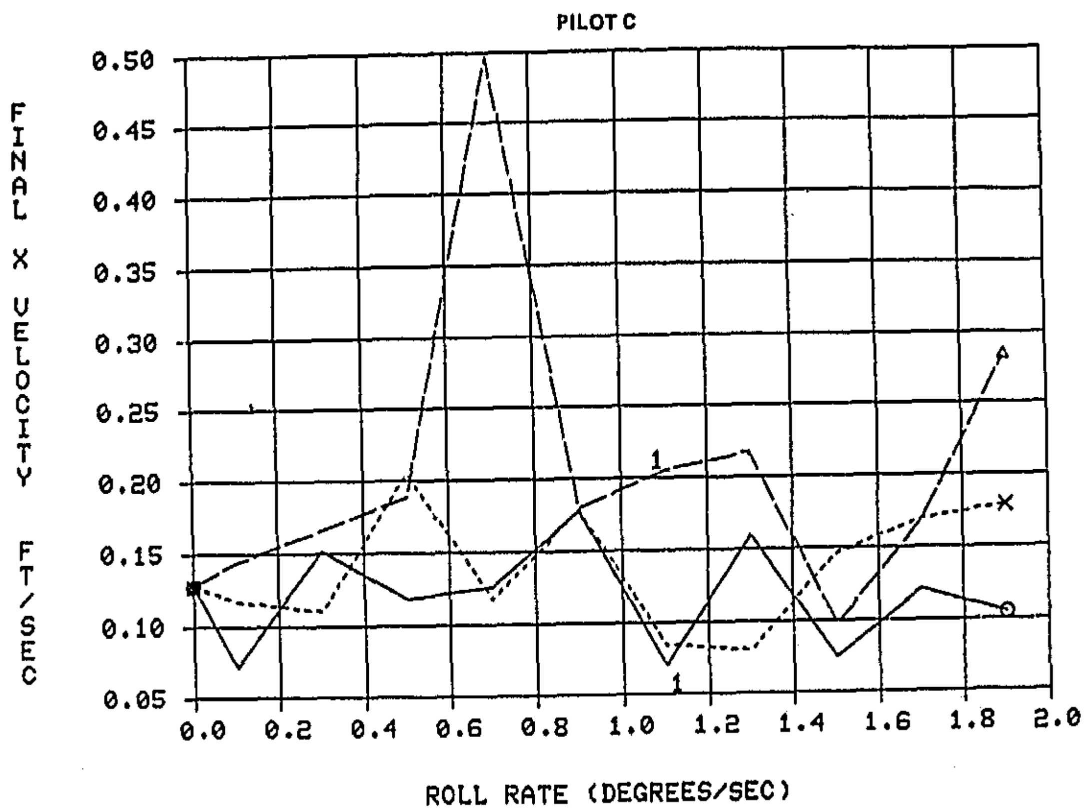

PILOT B
FUEL USED POUNDS
140
120
100
80
60
40
20
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

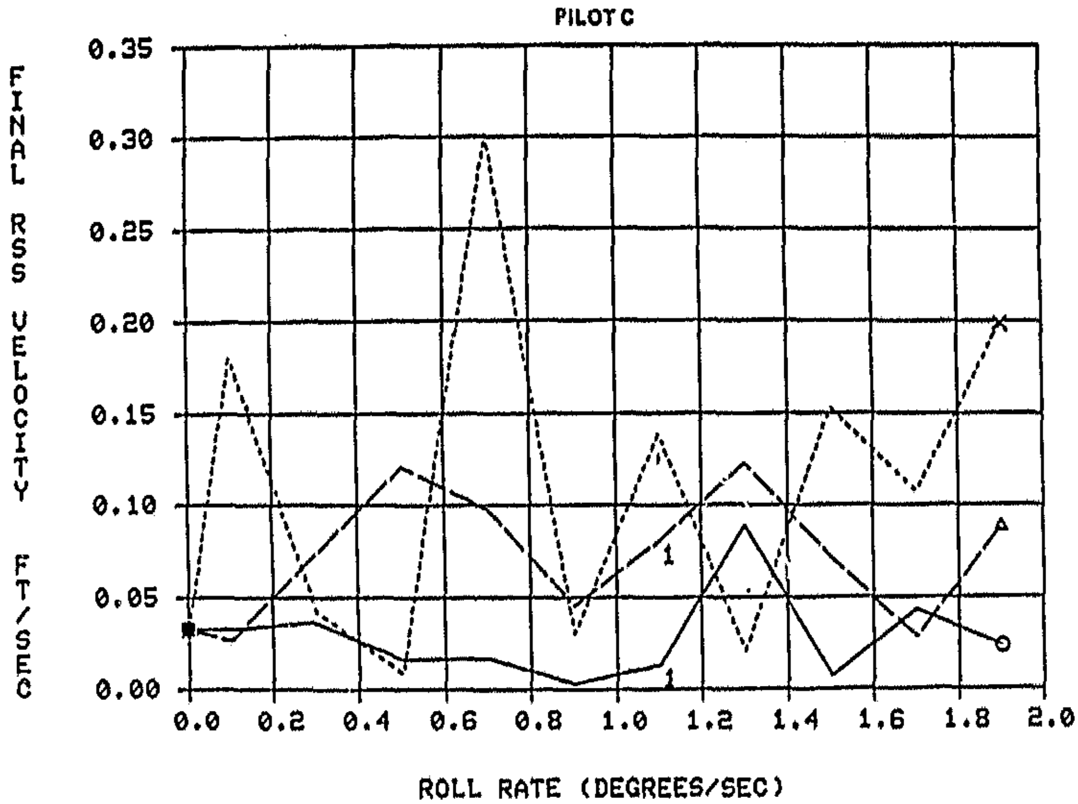

PILOT B
TIME REQUIRED SECONDS
1000
900
800
700
600
500
400
300
200
100
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

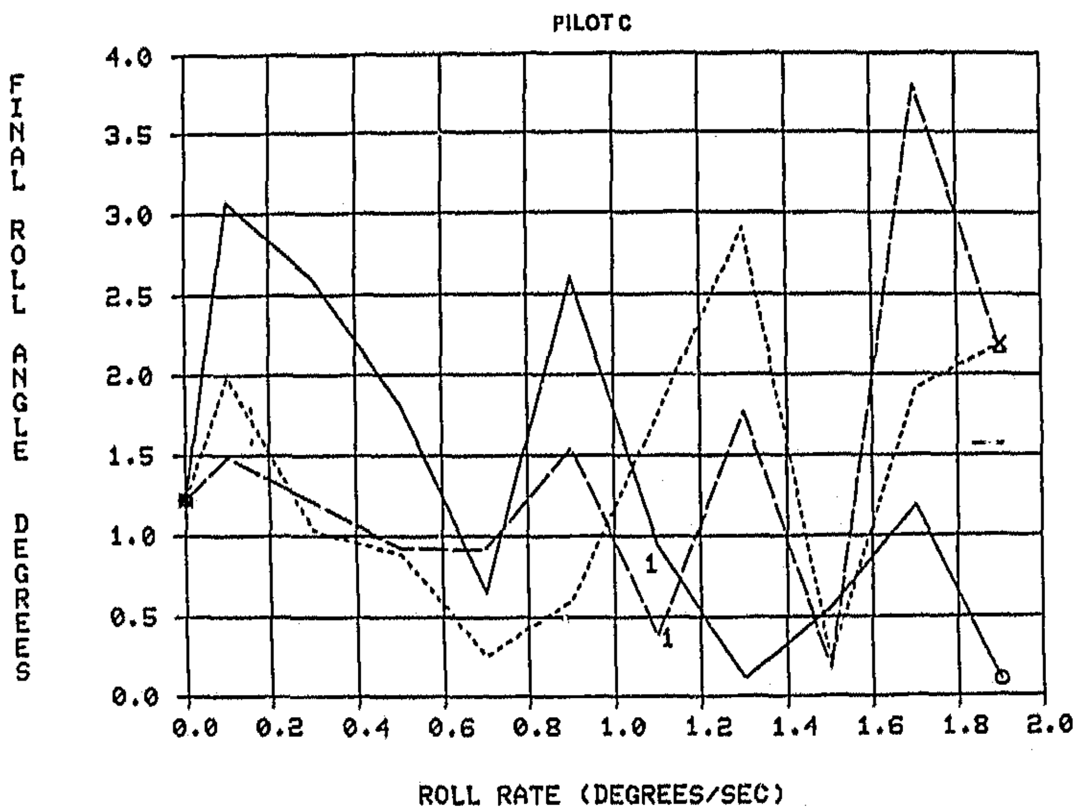

PILOT C
TIME REQUIRED SECONDS
ROLL RATE (DEGREES/SEC)

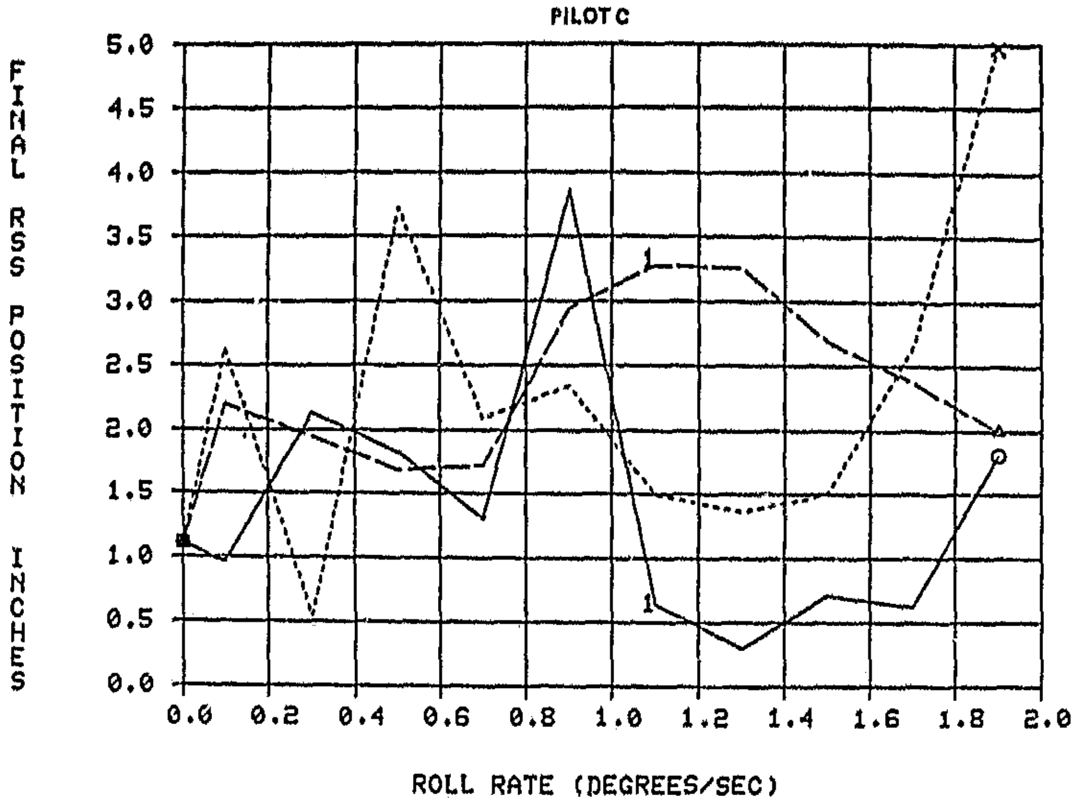

PILOT C
FUEL USED POUNDS
ROLL RATE (DEGREES/SEC)

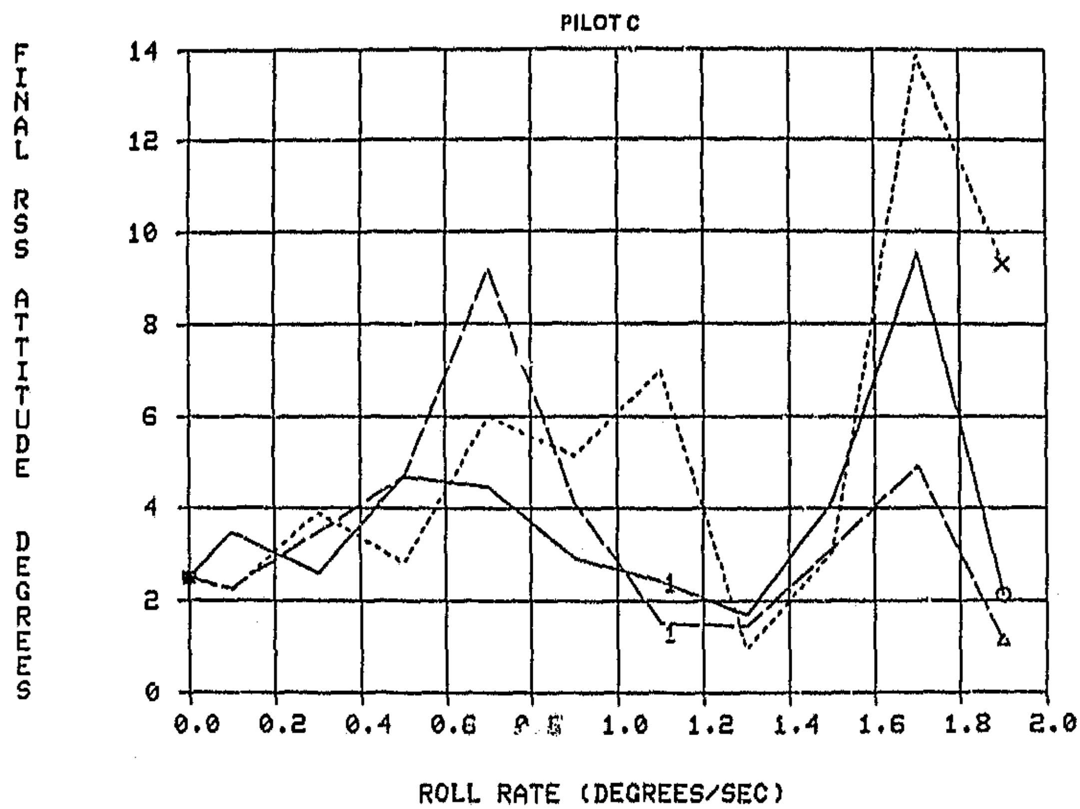

PILOT C
TOTAL # OF FIRINGS
12000
10000
8000
6000
4000
2000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

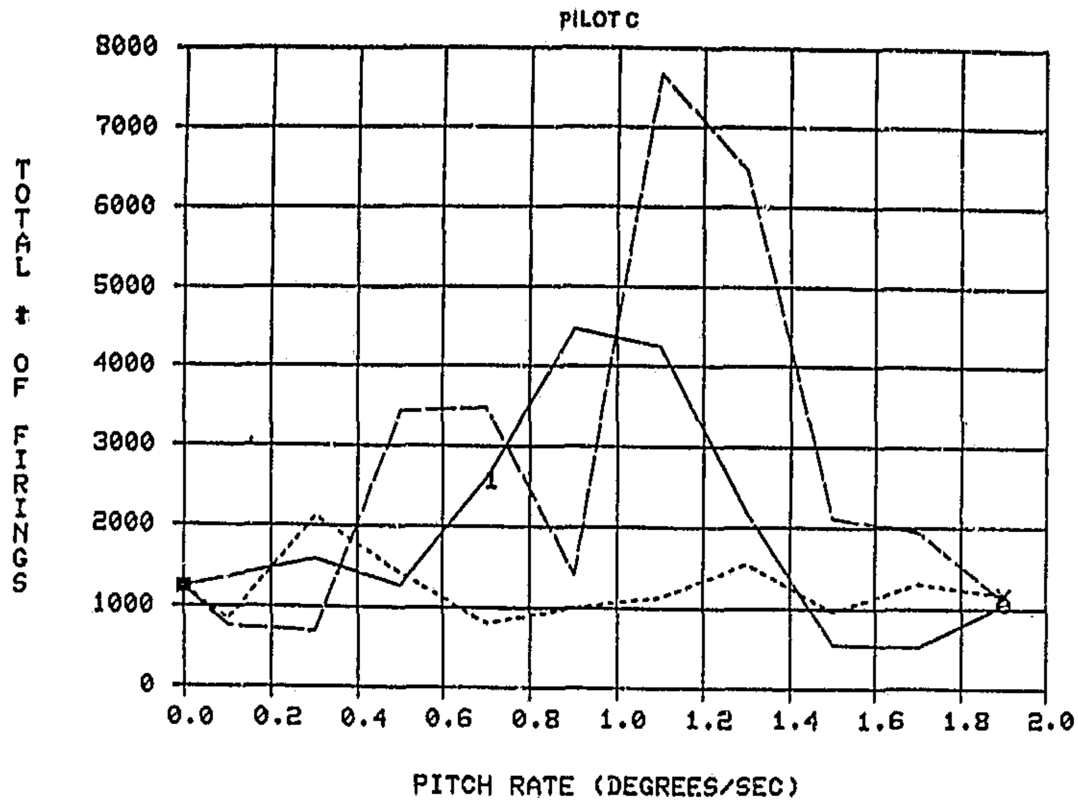

PILOT C
FINAL X VELOCITY FT/SEC
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

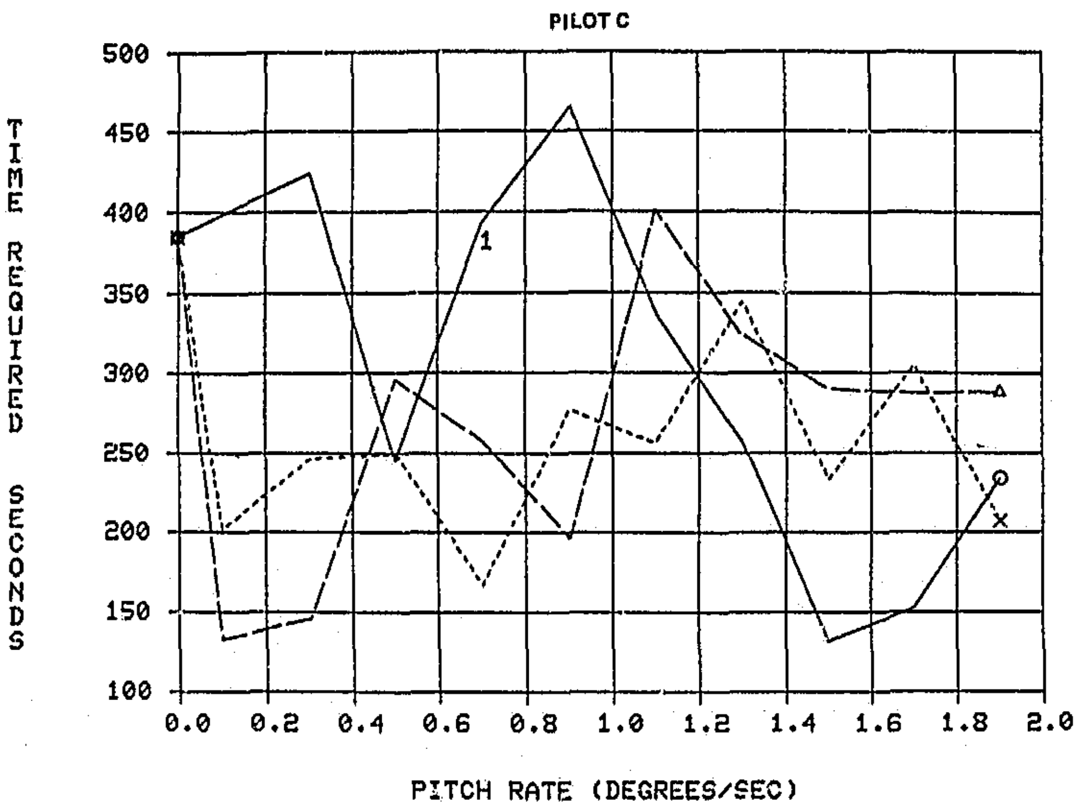

PILOT C
FINAL RSS VELOCITY FT/SEC
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)

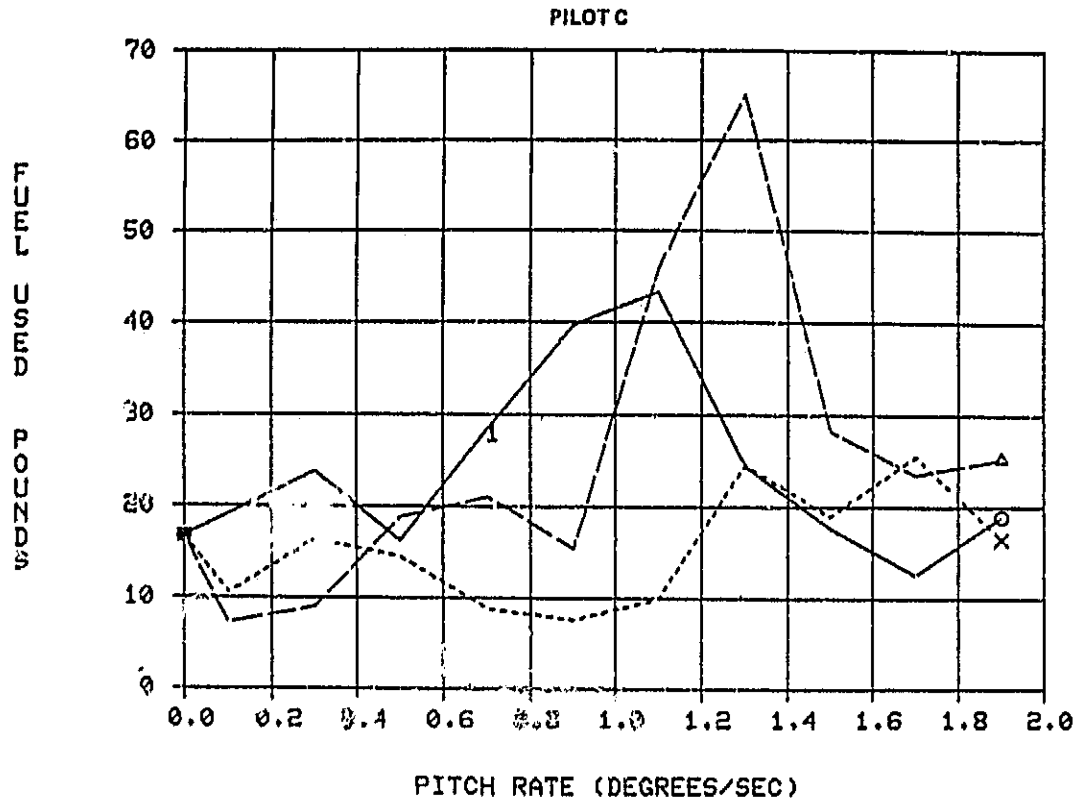

PILOT C
FINAL ROLL ANGLE DEGREES
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)

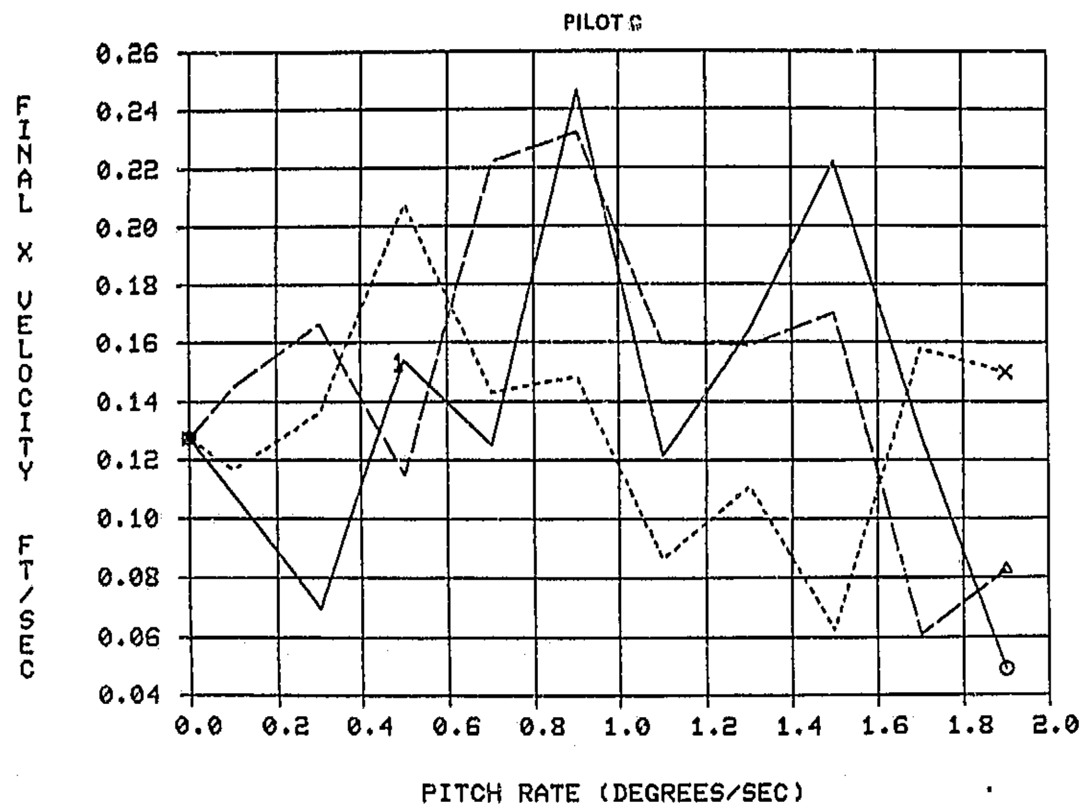

PILOT C
FINAL RSS POSITION INCHES
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

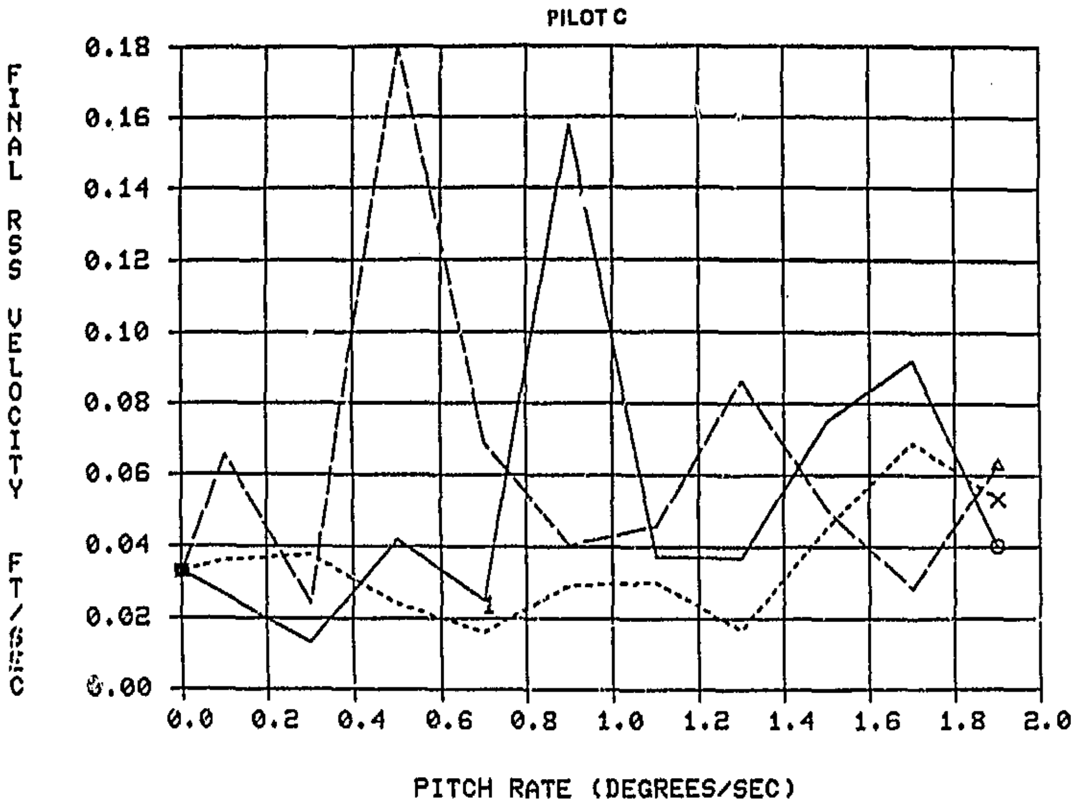

PILOT C
FINAL RSS ATTITUDE DEGREES
14
12
10
8
6
4
2
0
0.0
0.2
0.4
0.6
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

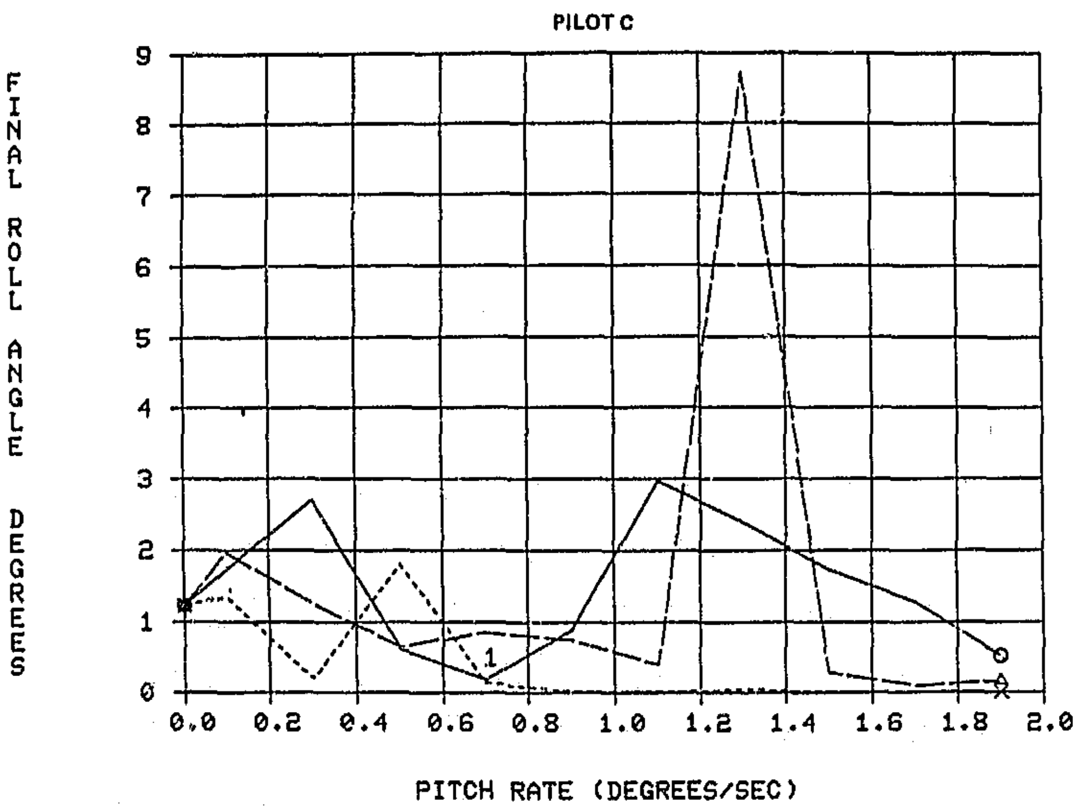

PILOT C
TOTAL # OF FIRINGS
8000
7000
6000
5000
4000
3000
2000
1000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)

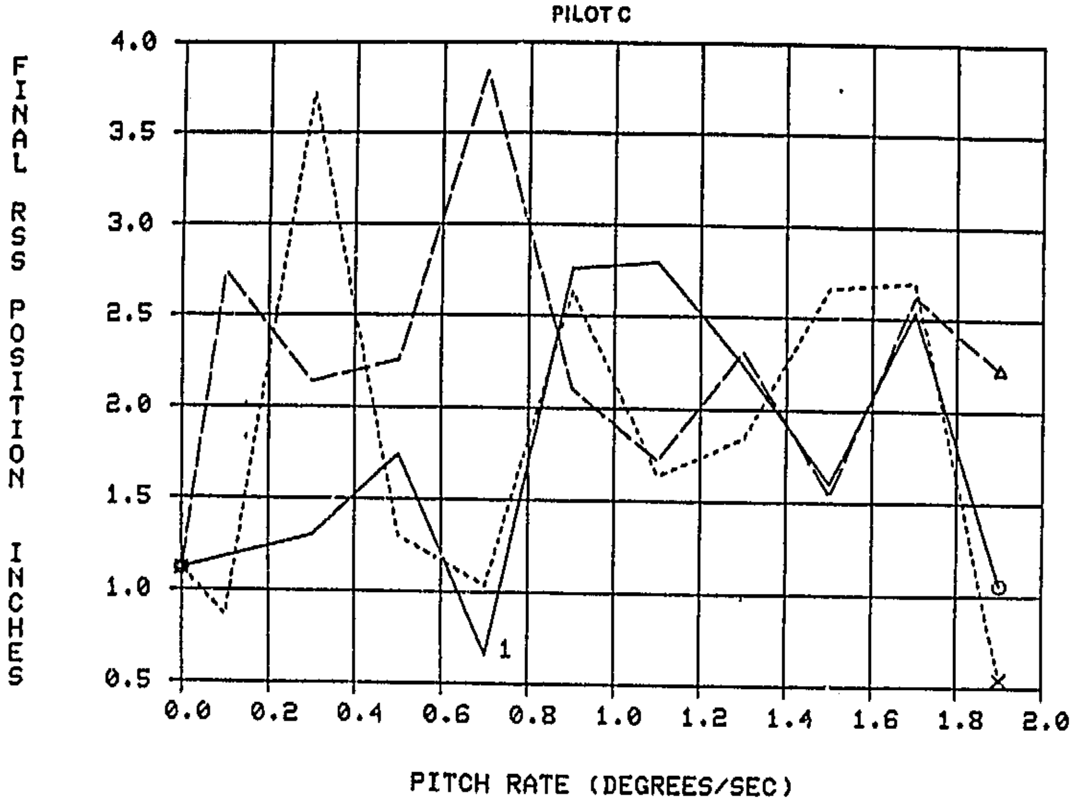

PILOT C
TIME REQUIRED SECONDS
500
450
400
350
300
250
200
150
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)

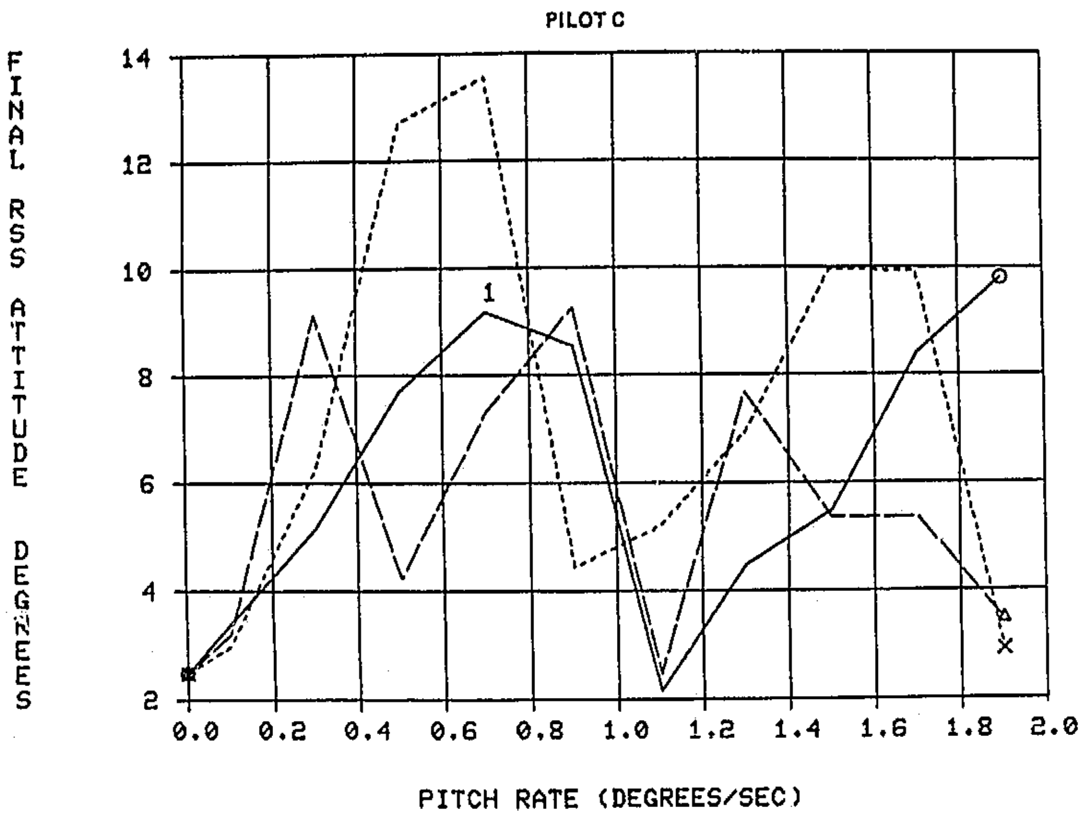

PILOT C
FUEL USED POUNDS
70
60
50
40
30
20
10
0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

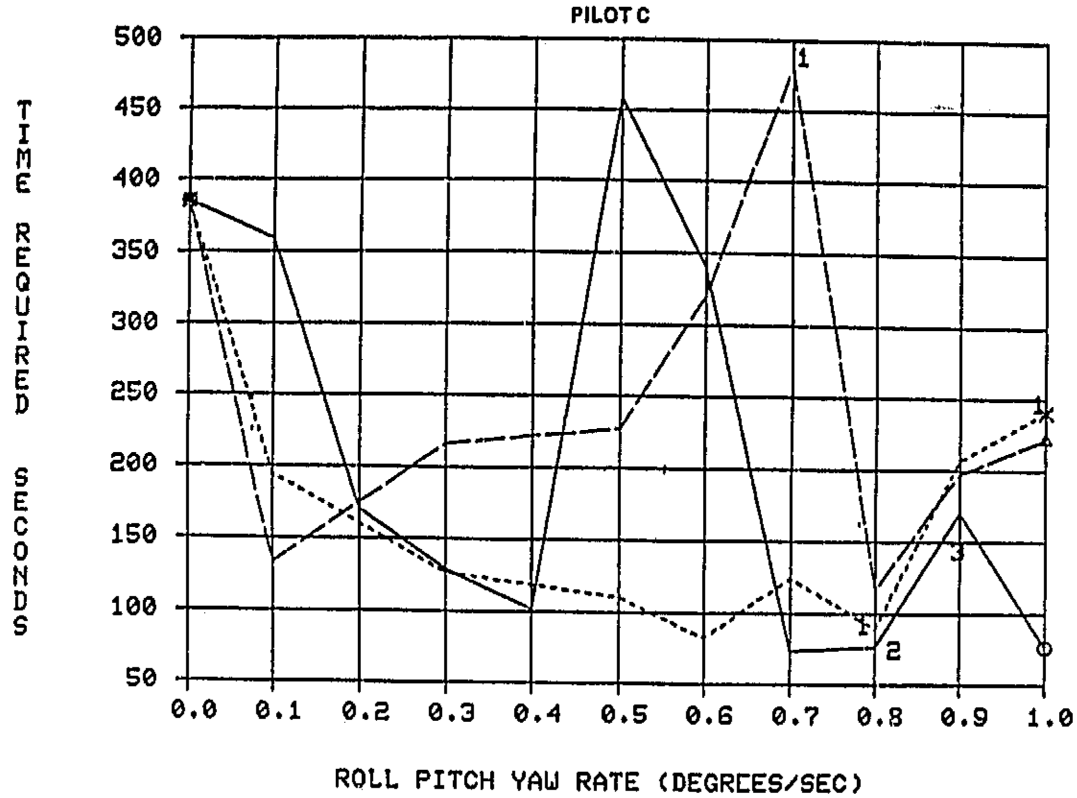

PILOT C
FINAL X VELOCITY FT/SEC
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

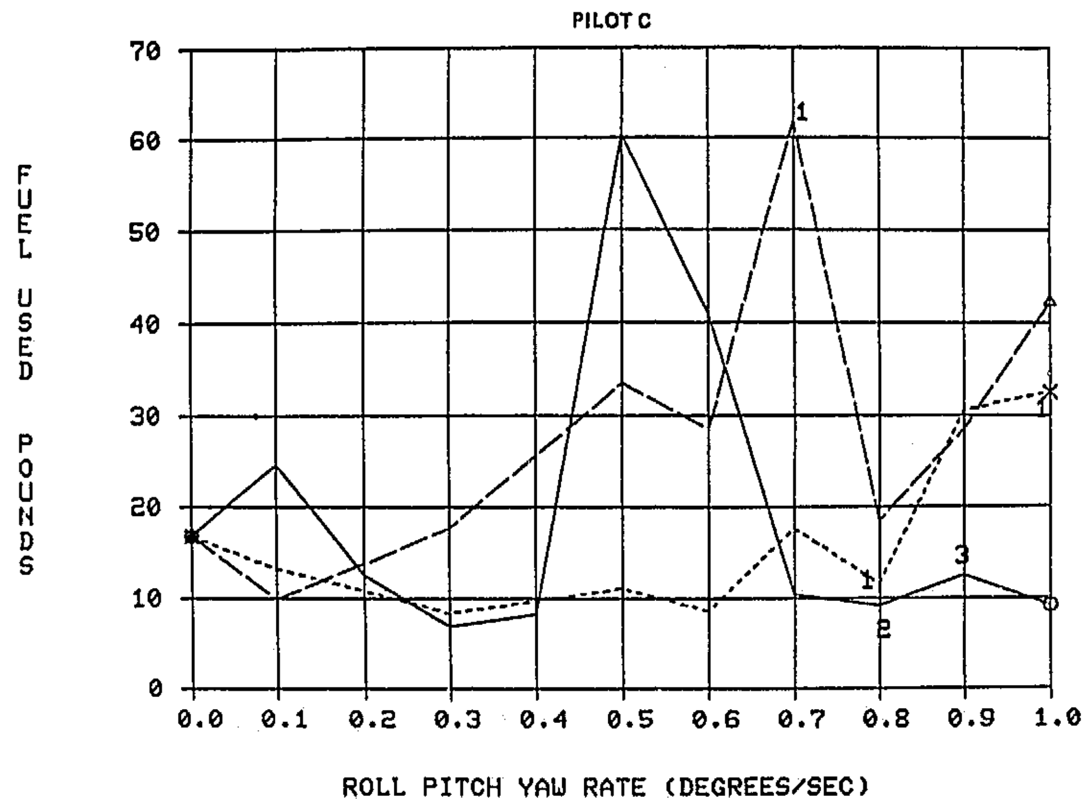

PILOT C
FINAL RSS VELOCITY FT/SEC
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

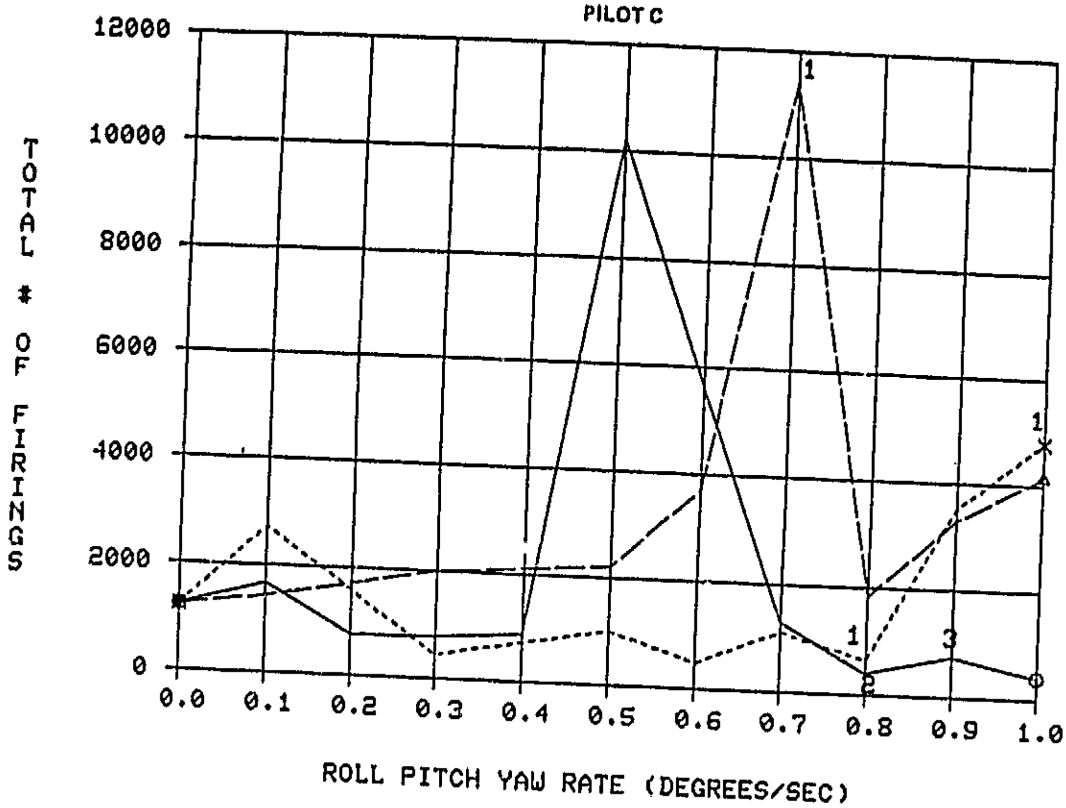

PILOT C
FINAL ROLL ANGLE DEGREES
9
8
7
6
5
4
3
2
1
0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

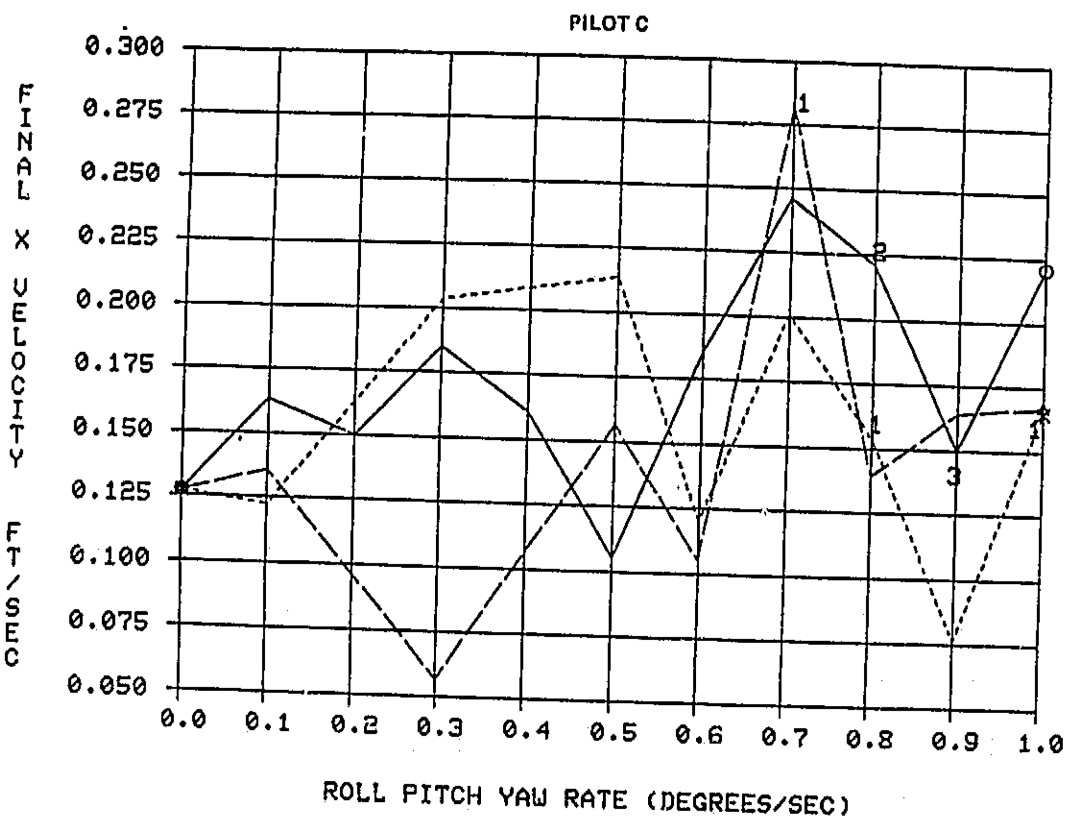

PILOT C
FINAL RSS POSITION INCHES
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
1
PITCH RATE (DEGREES/SEC)

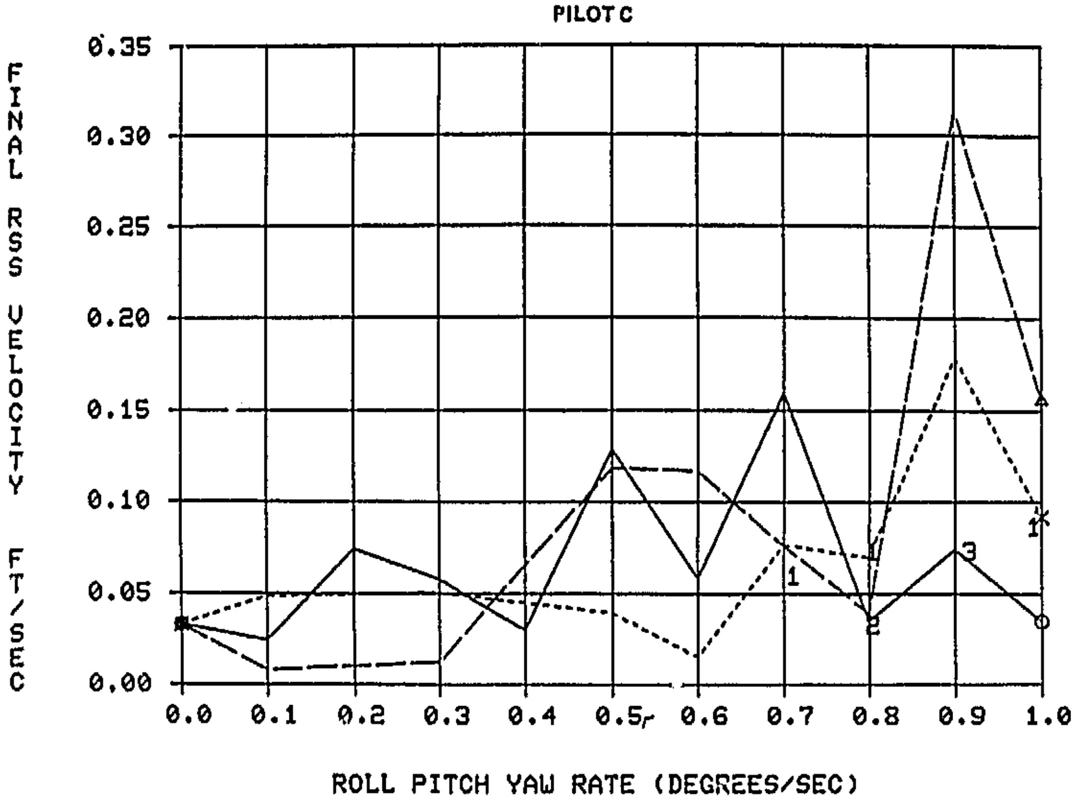

PILOT C
FINAL RSS ATTITUDE DEGREES
14
12
10
8
6
4
2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
1
PITCH RATE (DEGREES/SEC)

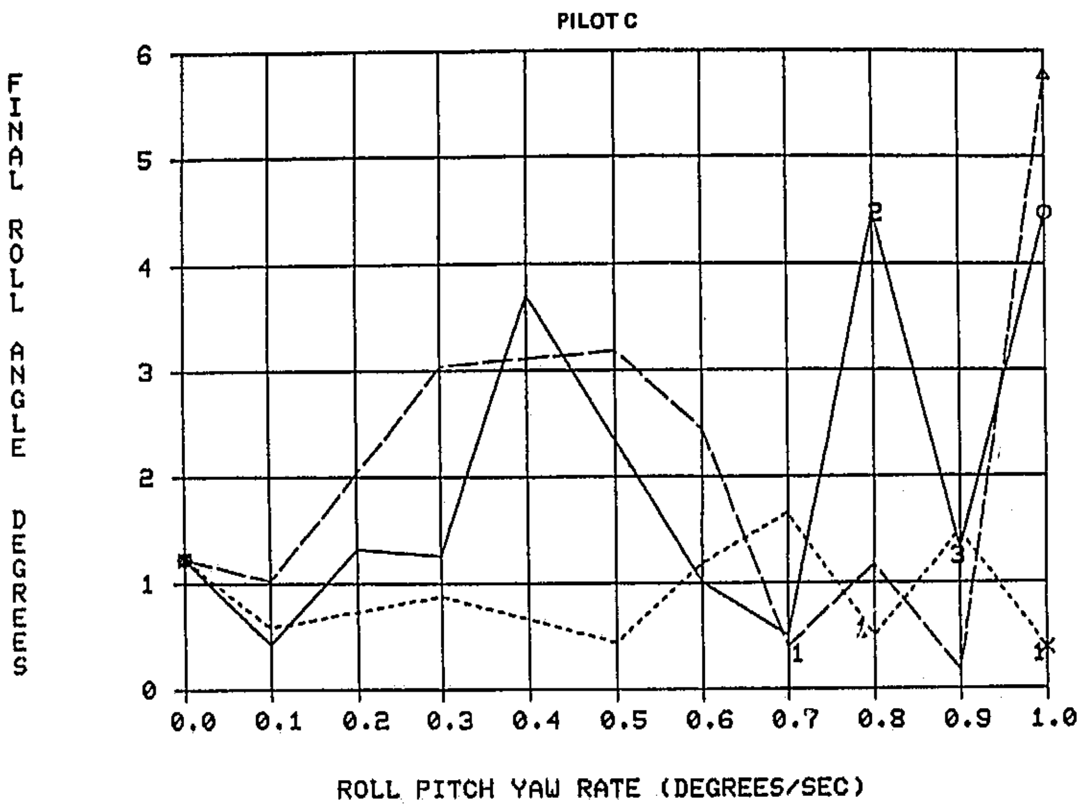

PILOT C
TIME REQUIRED SECONDS
500
450
400
350
300
250
200
150
100
50
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

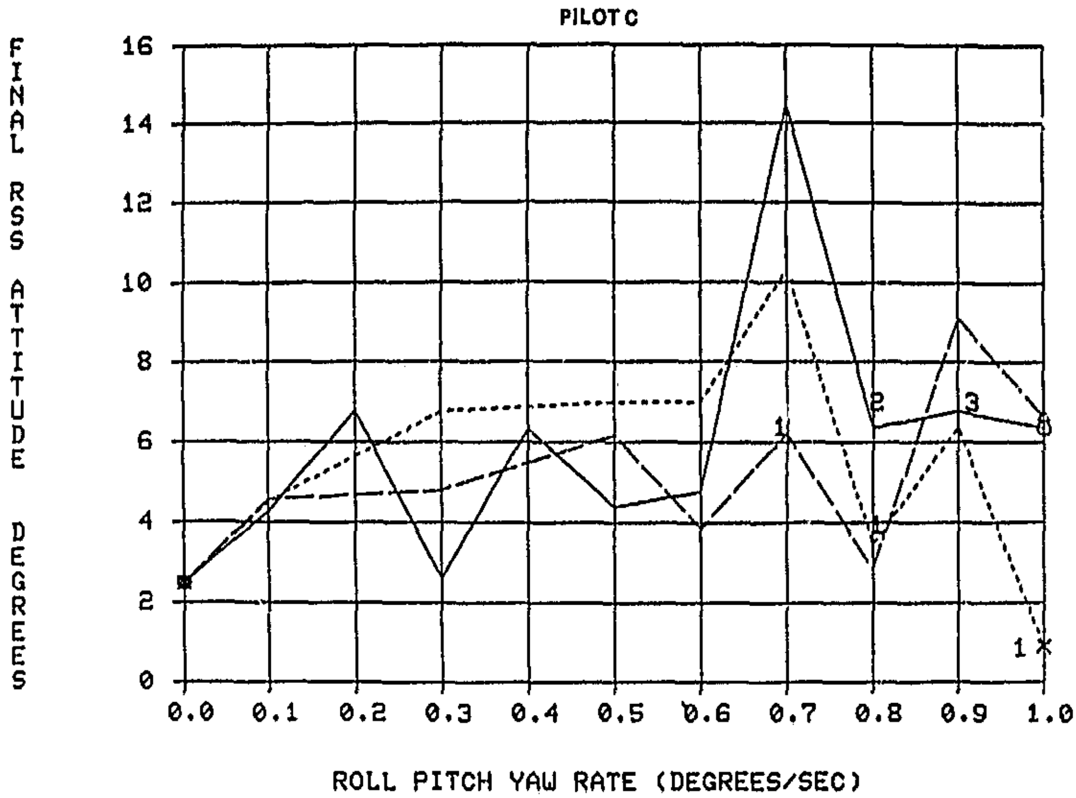

PILOT C
FUEL USED POUNDS
70
60
50
40
30
20
10
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

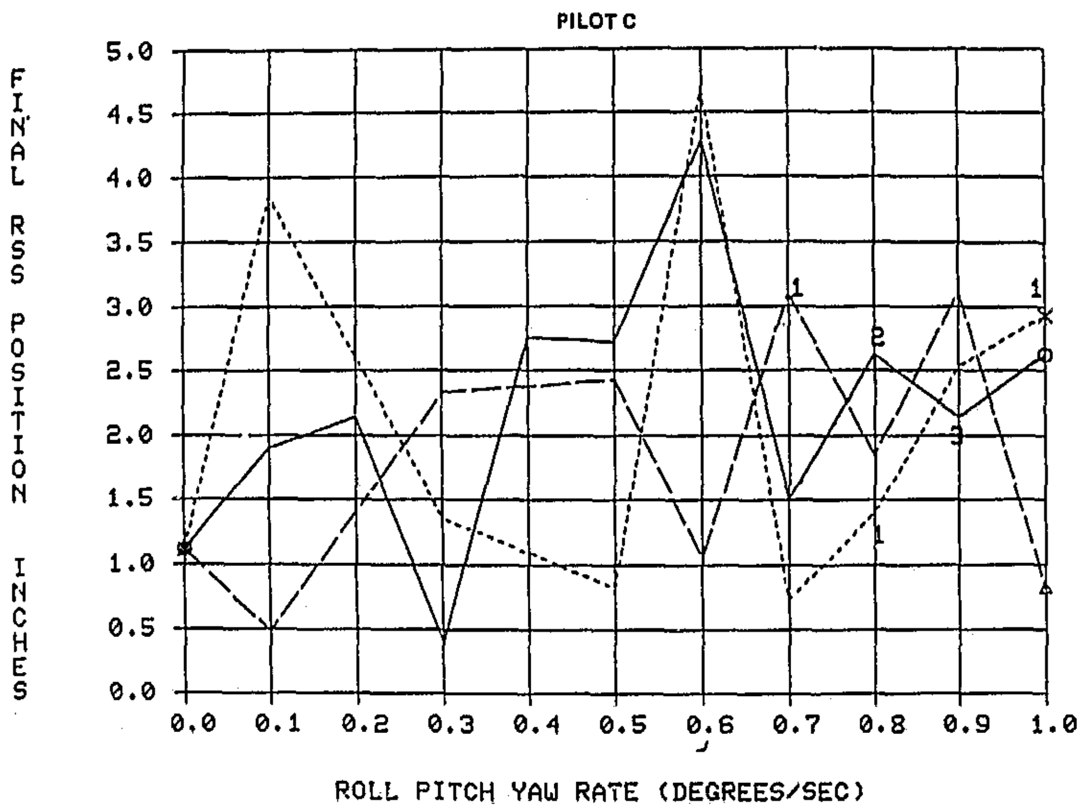

PILOT C
TOTAL # OF FIRINGS
12000
10000
8000
6000
4000
2000
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

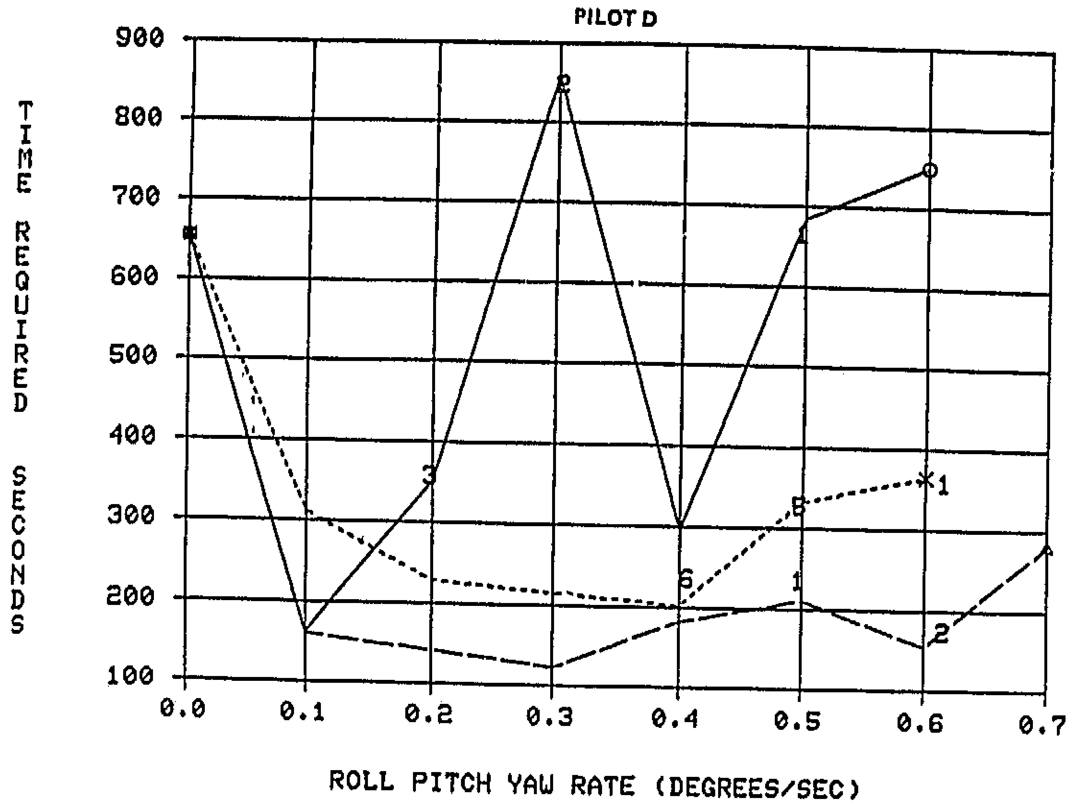

PILOT C
FINAL X VELOCITY FT/SEC
0.300
0.275
0.250
0.225
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

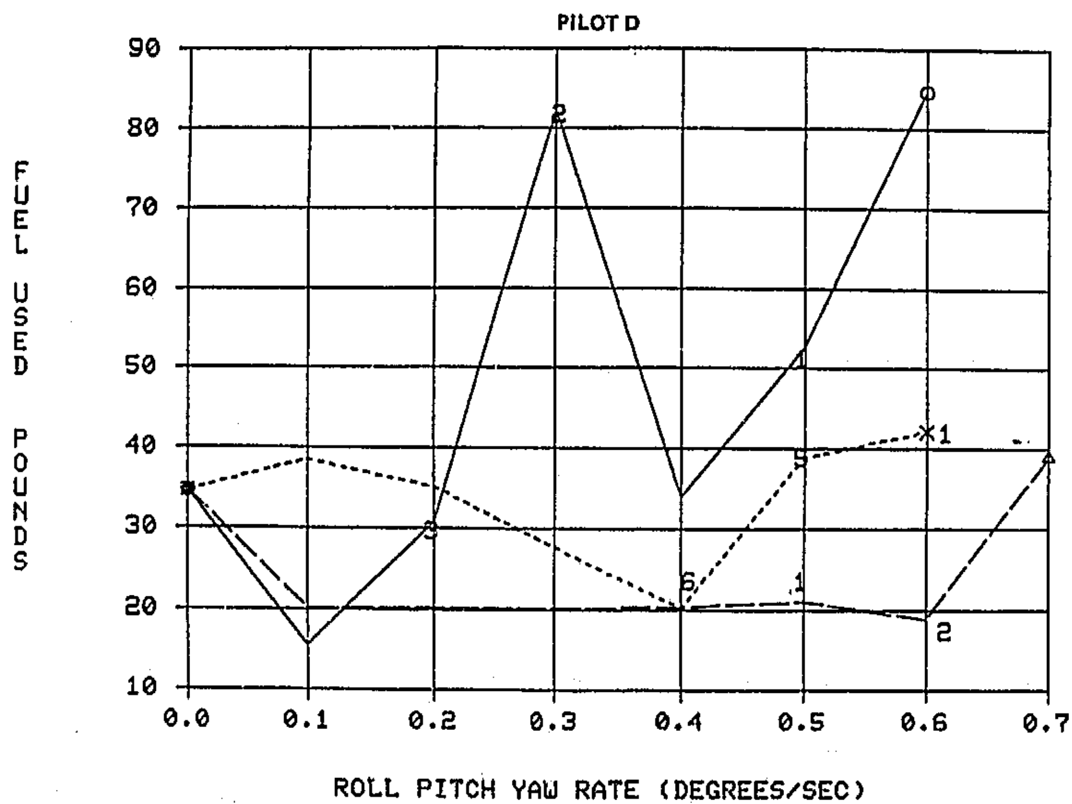

PILOT C
FINAL RSS VELOCITY FT/SEC
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

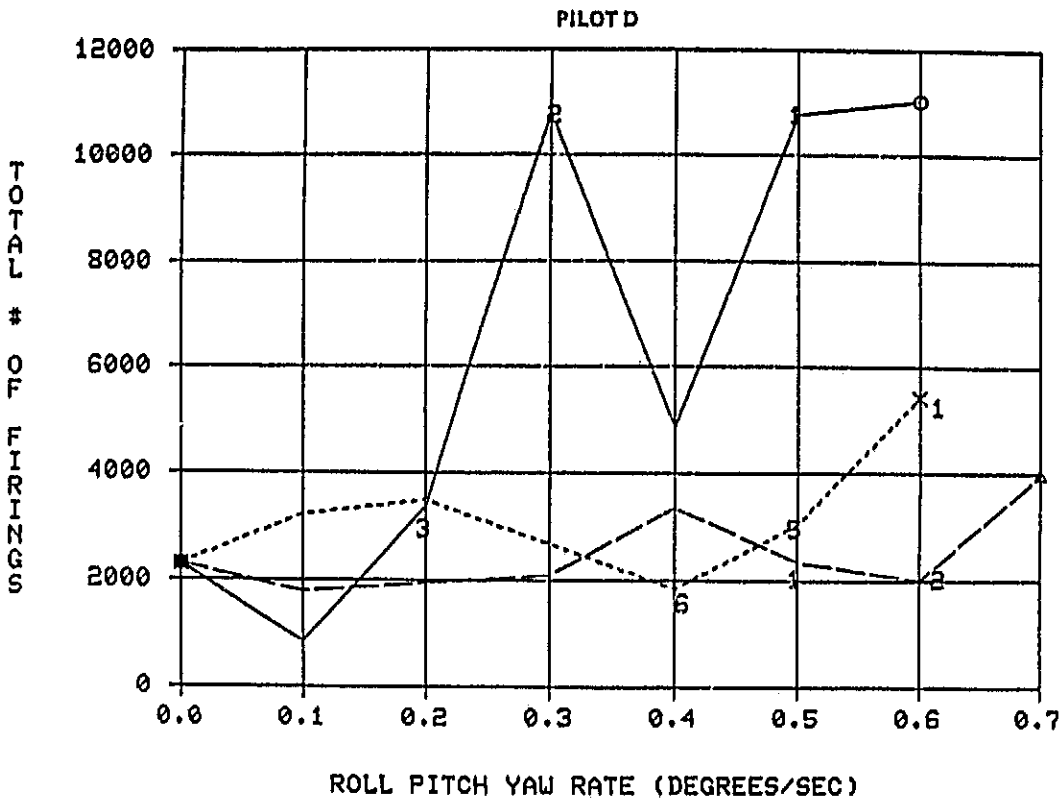

PILOT C
FINAL ROLL ANGLE DEGREES
6
5
4
3
2
1
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

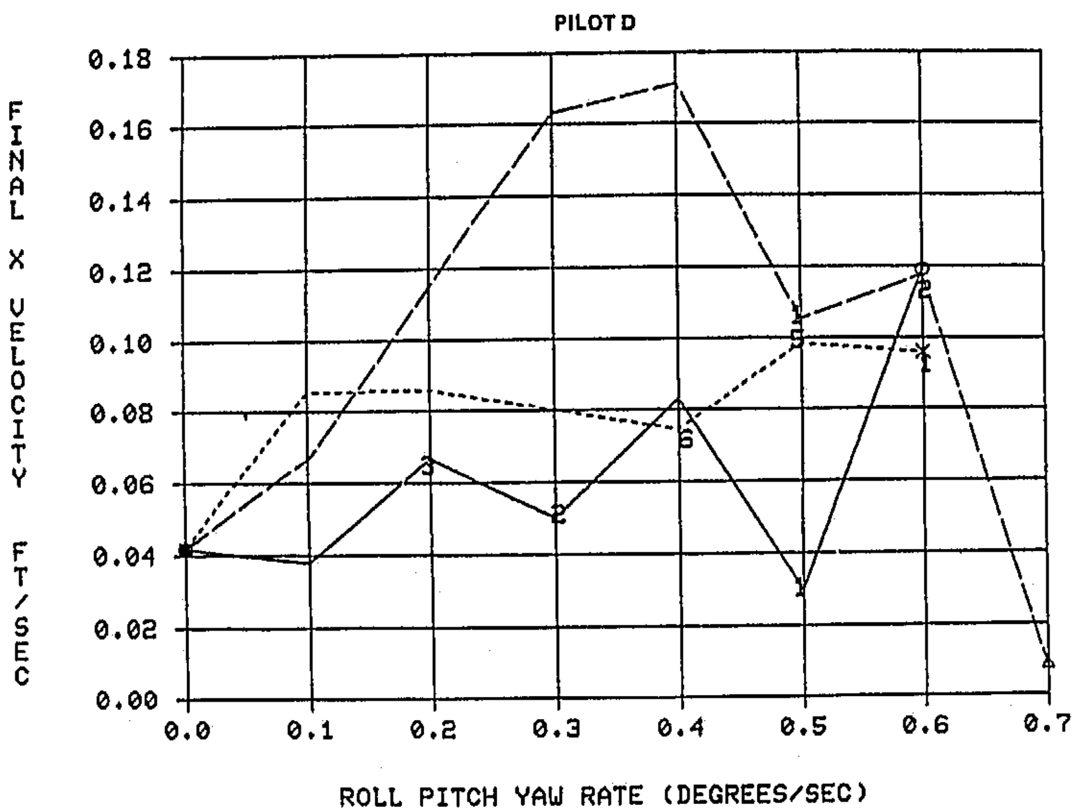

PILOT C
FINAL RSS ATTITUDE DEGREES
16
14
12
10
8
6
4
2
0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

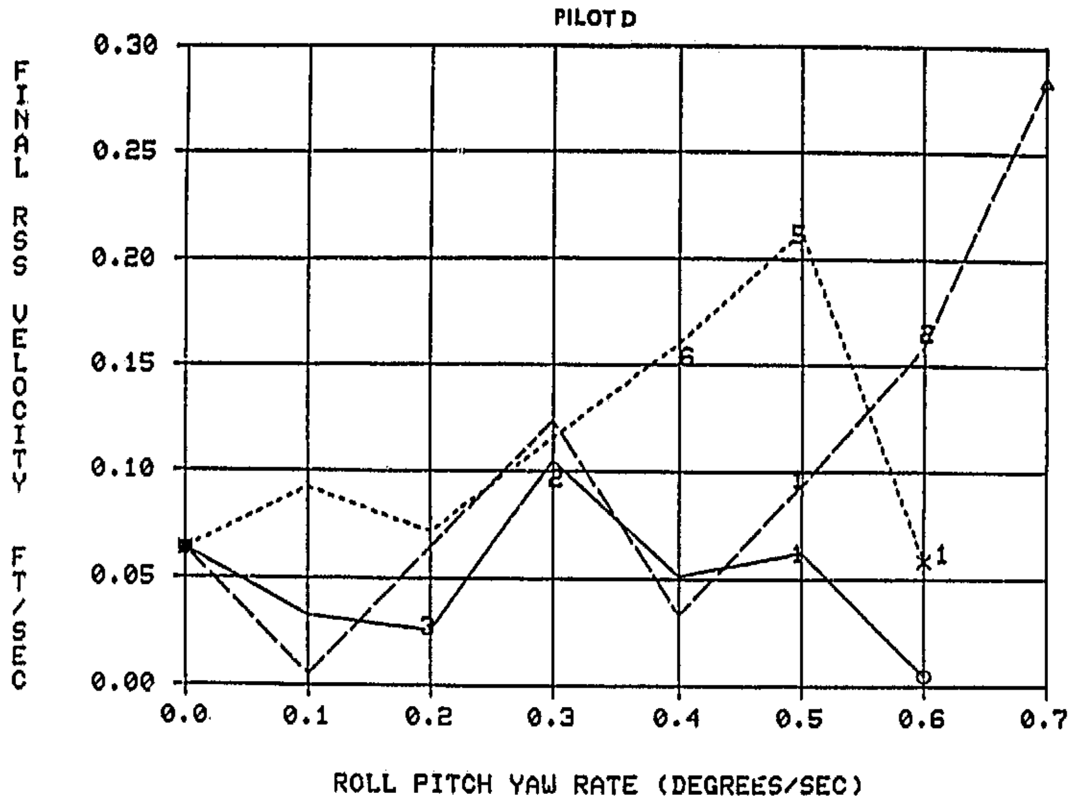

PILOT C
FINAL RSS POSITION INCHES
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
ROLL PITCH YAW RATE (DEGREES/SEC)

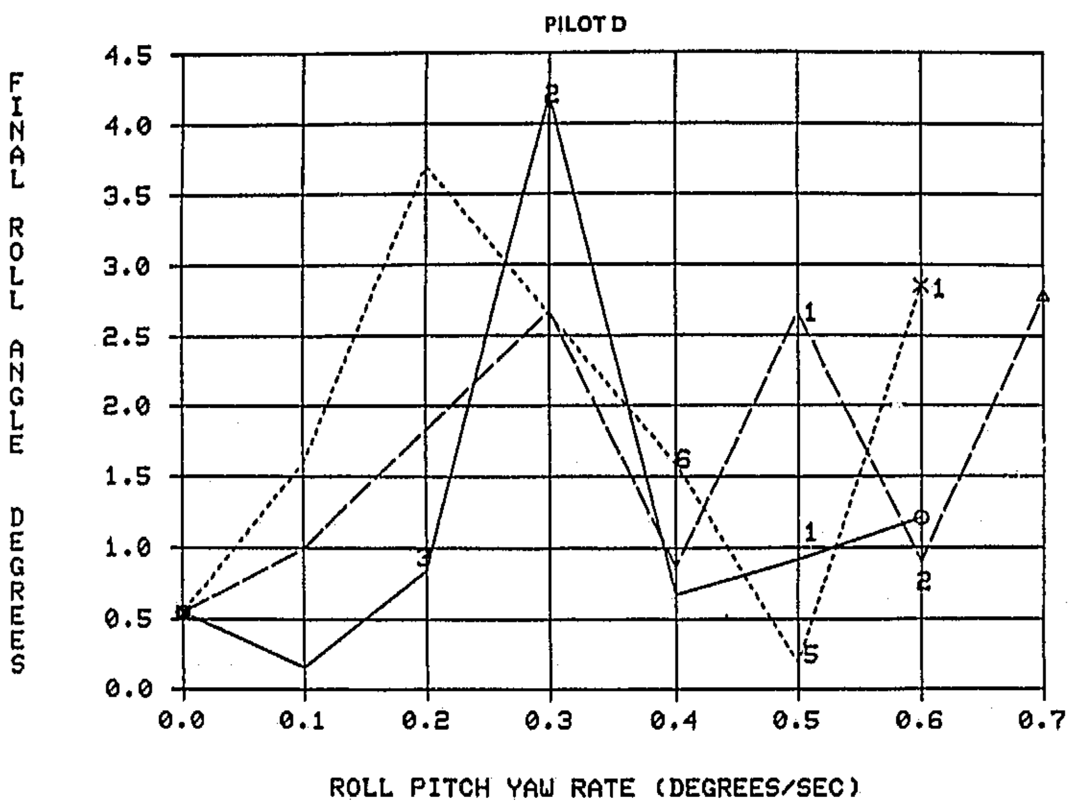

PILOT D
900
800
700
600
500
400
300
200
100
TIME REQUIRED SECONDS
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

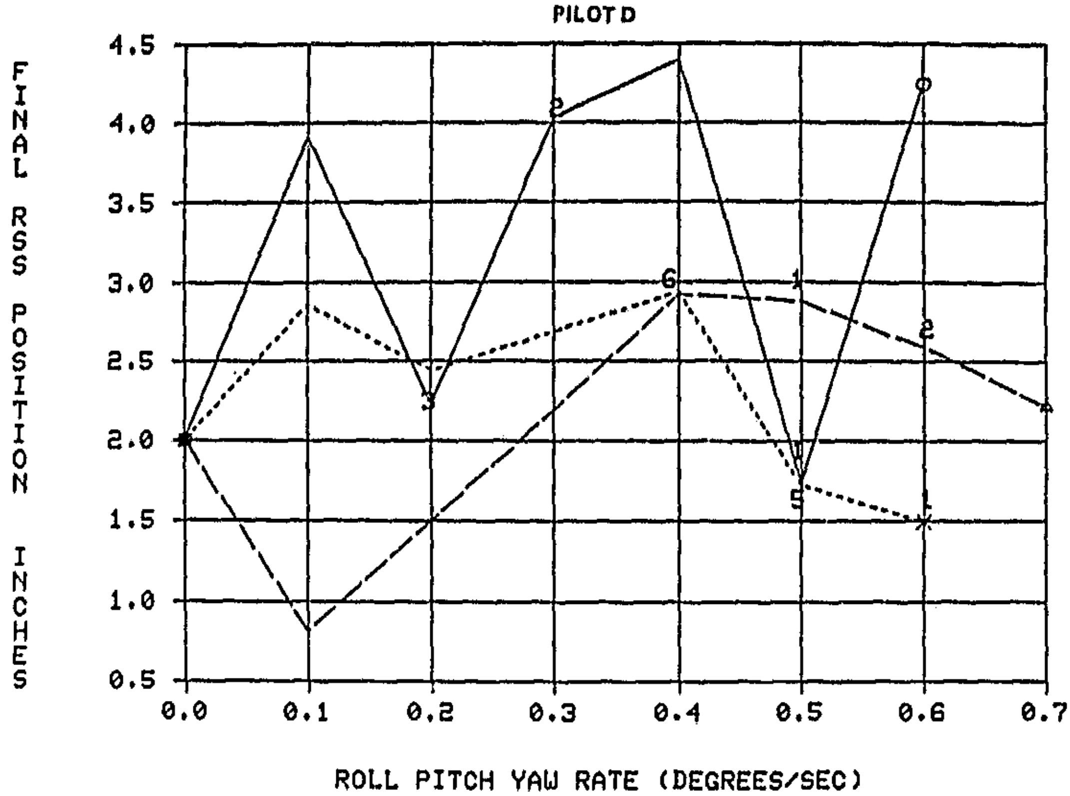

PILOT D
90
80
70
60
50
40
30
20
10
FUEL USED POUNDS
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

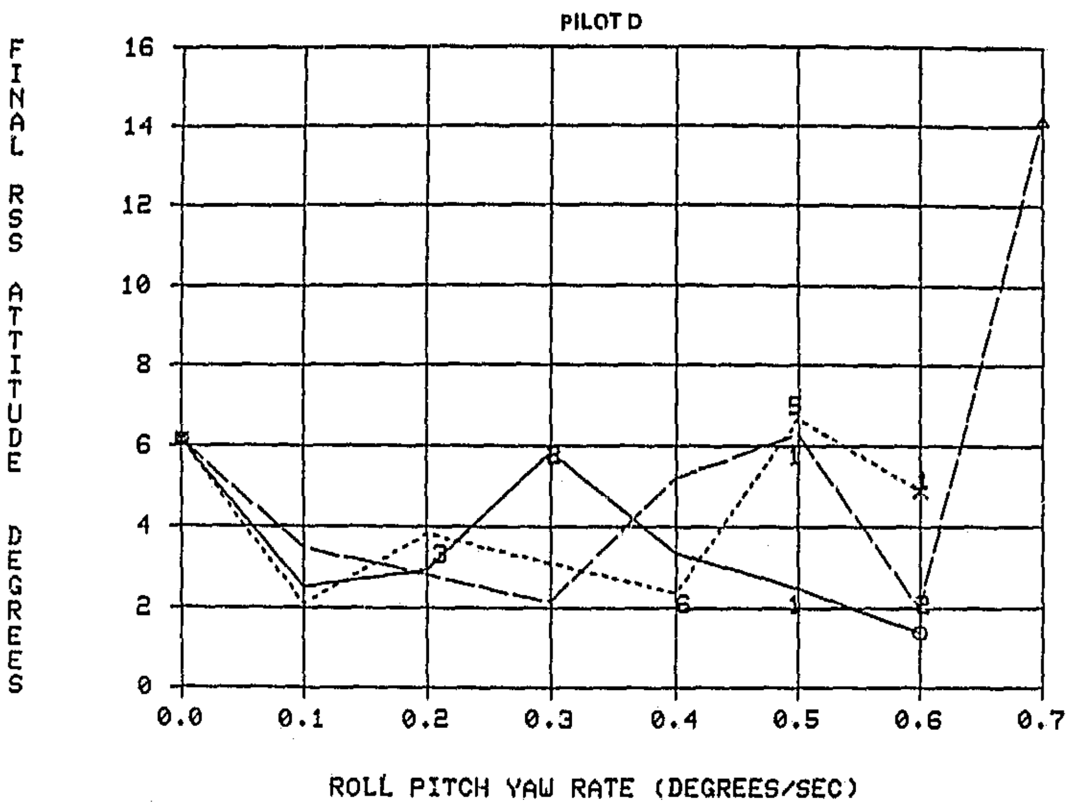

PILOT D
12000
10000
8000
6000
4000
2000
0
TOTAL # OF FIRINGS
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

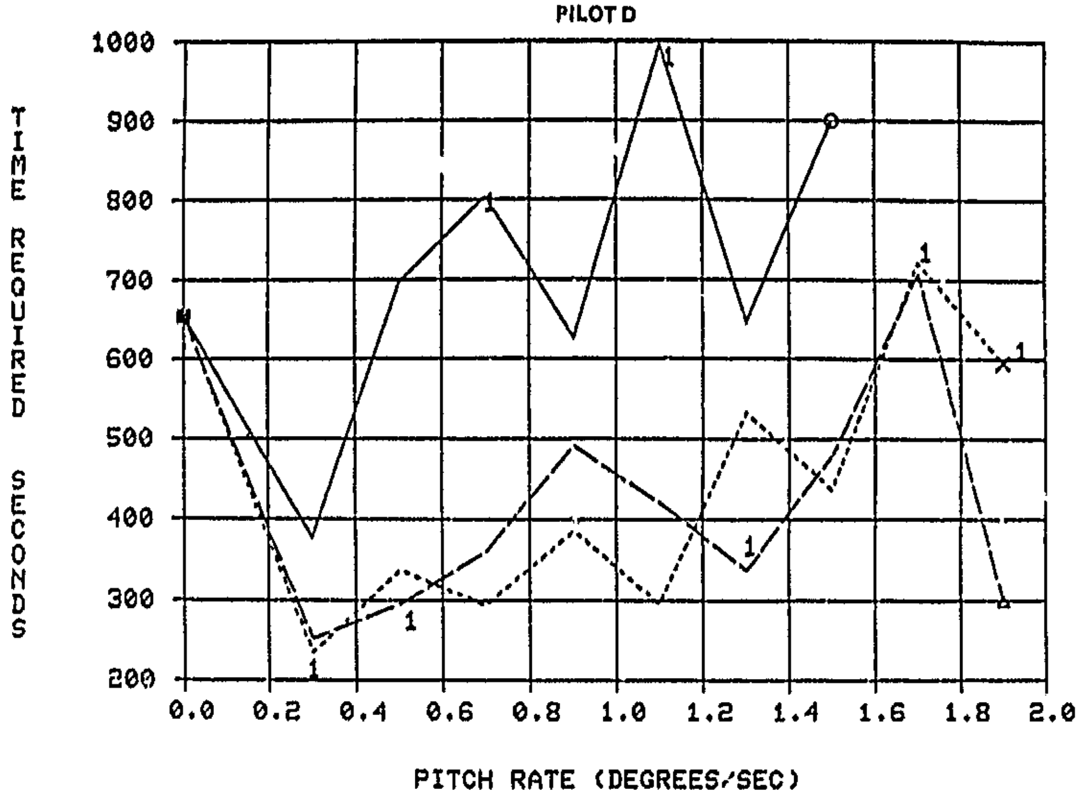

PILOT D
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
FINAL X VELOCITY FT/SEC
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

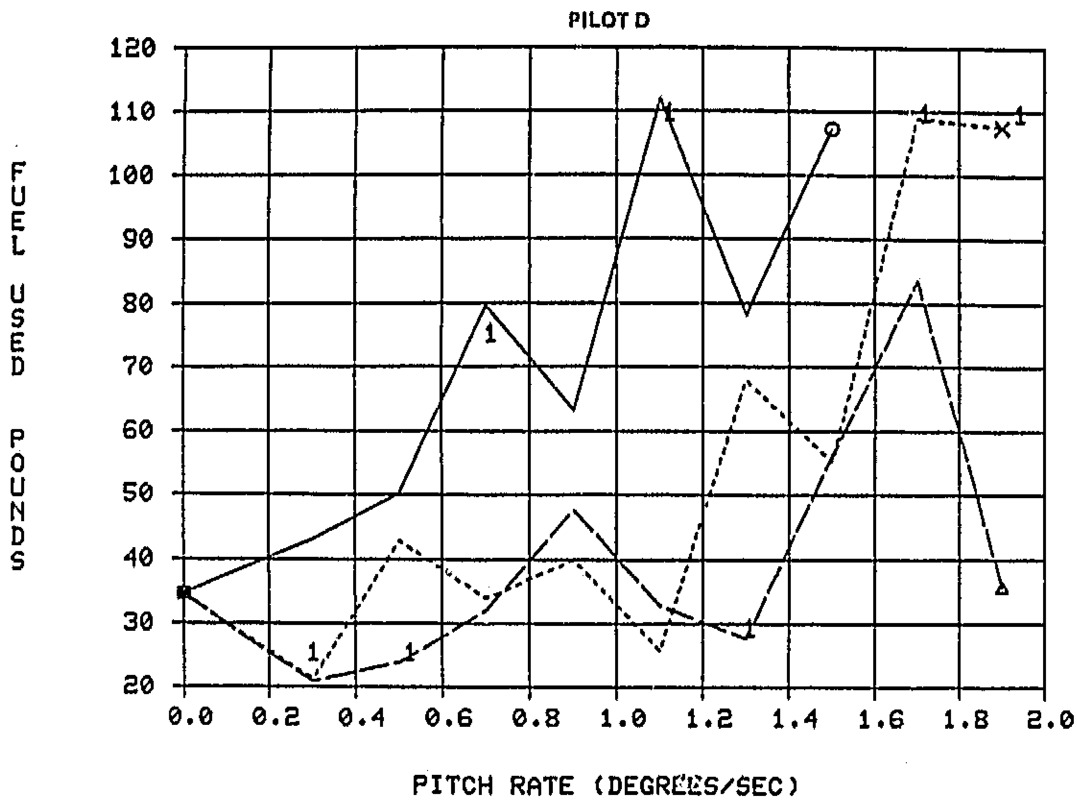

PILOT D
FINAL RSS VELOCITY FT/SEC
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

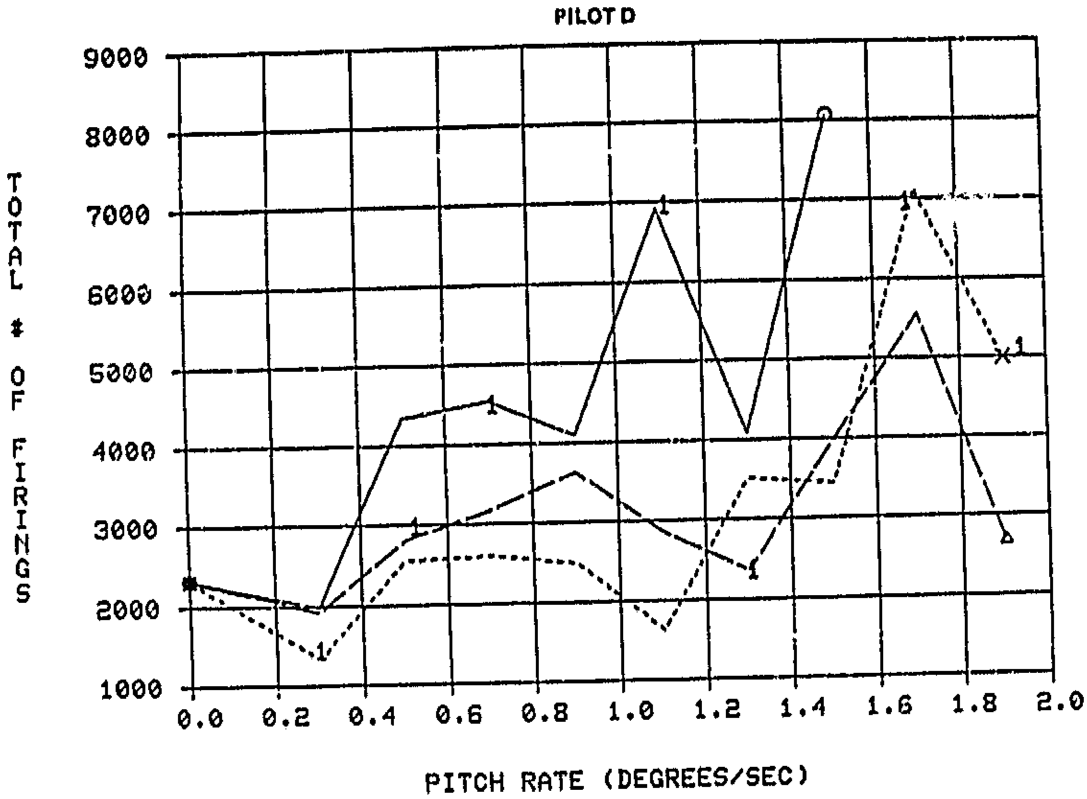

PILOT D
FINAL ROLL ANGLE DEGREES
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

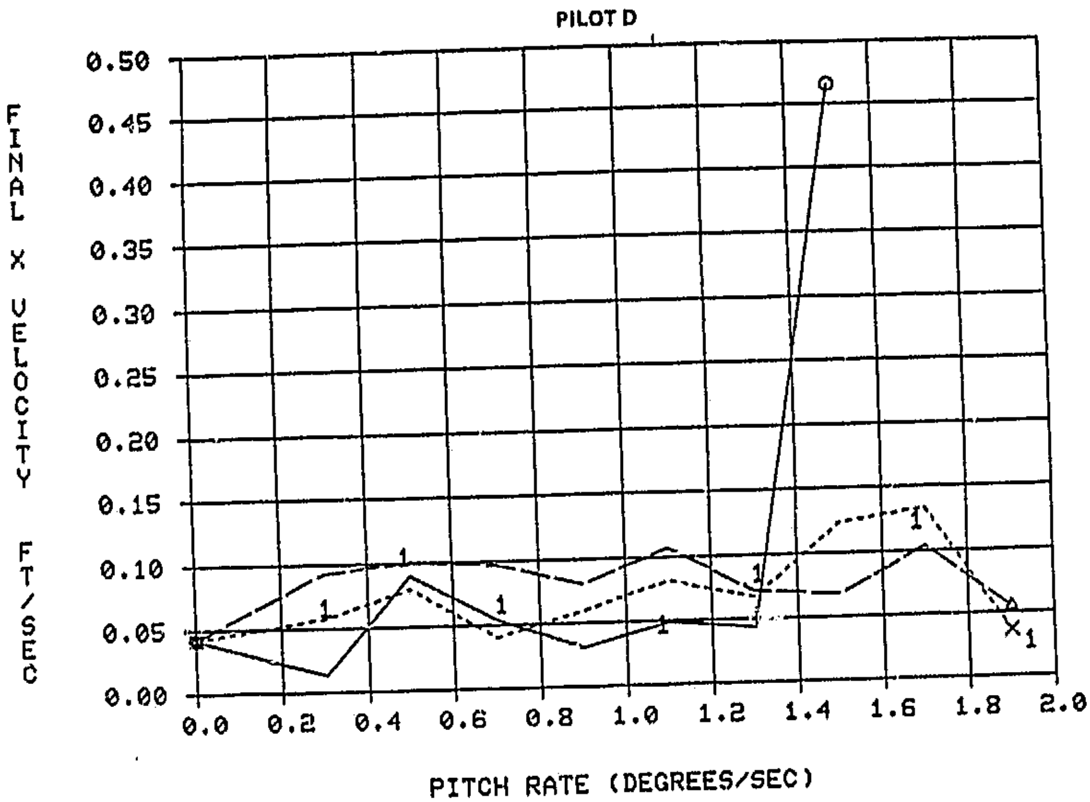

PILOT D
FINAL RSS POSITION INCHES
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

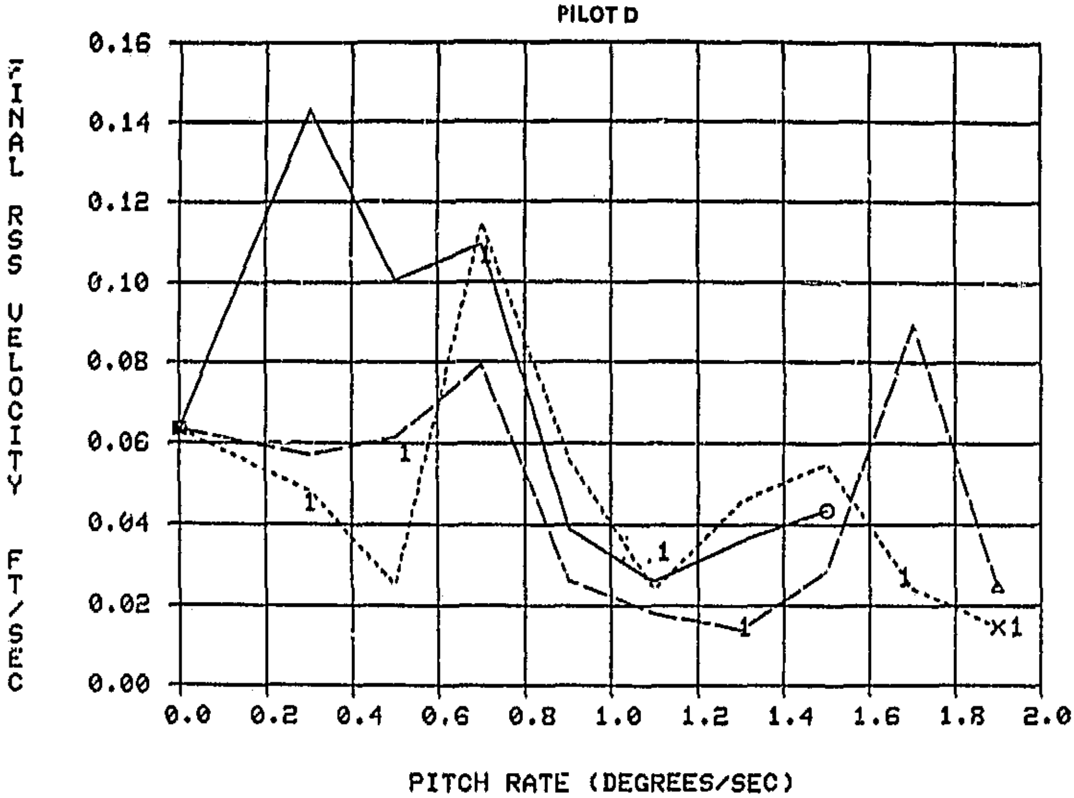

PILOT D
FINAL RSS ATTITUDE DEGREES
16
14
12
10
8
6
4
2
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ROLL PITCH YAW RATE (DEGREES/SEC)

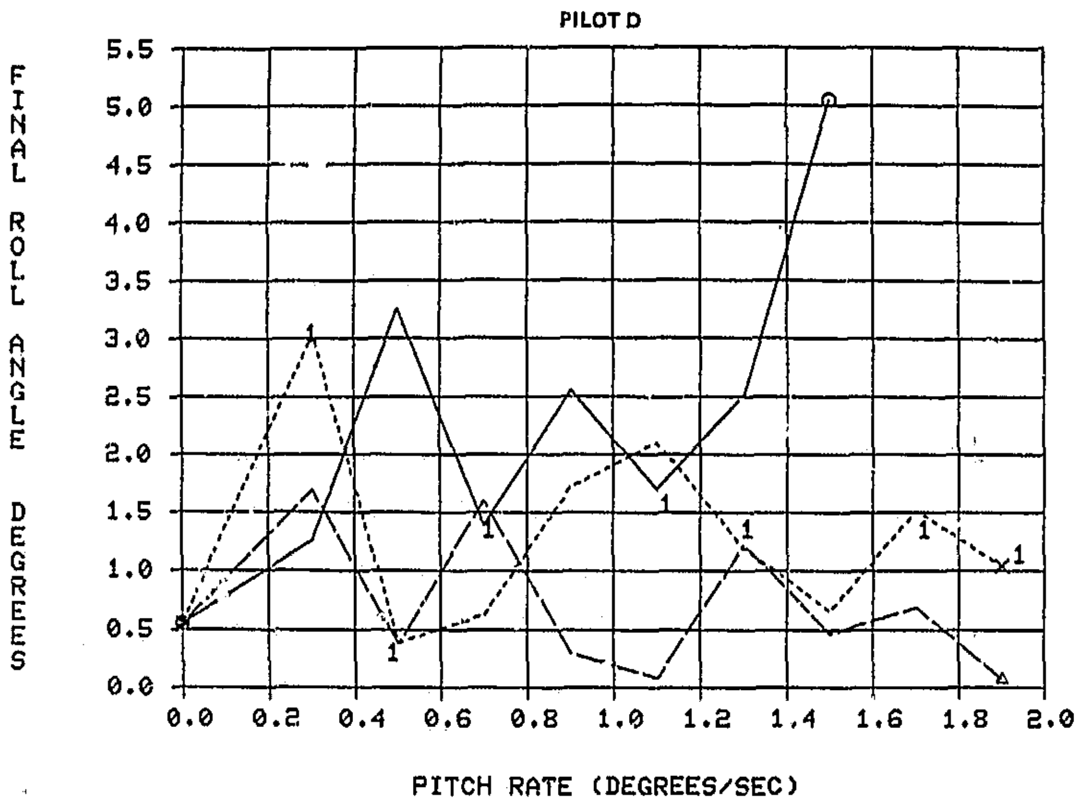

PILOT D
TIME REQUIRED SECONDS
1000
900
800
700
600
500
400
300
200
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

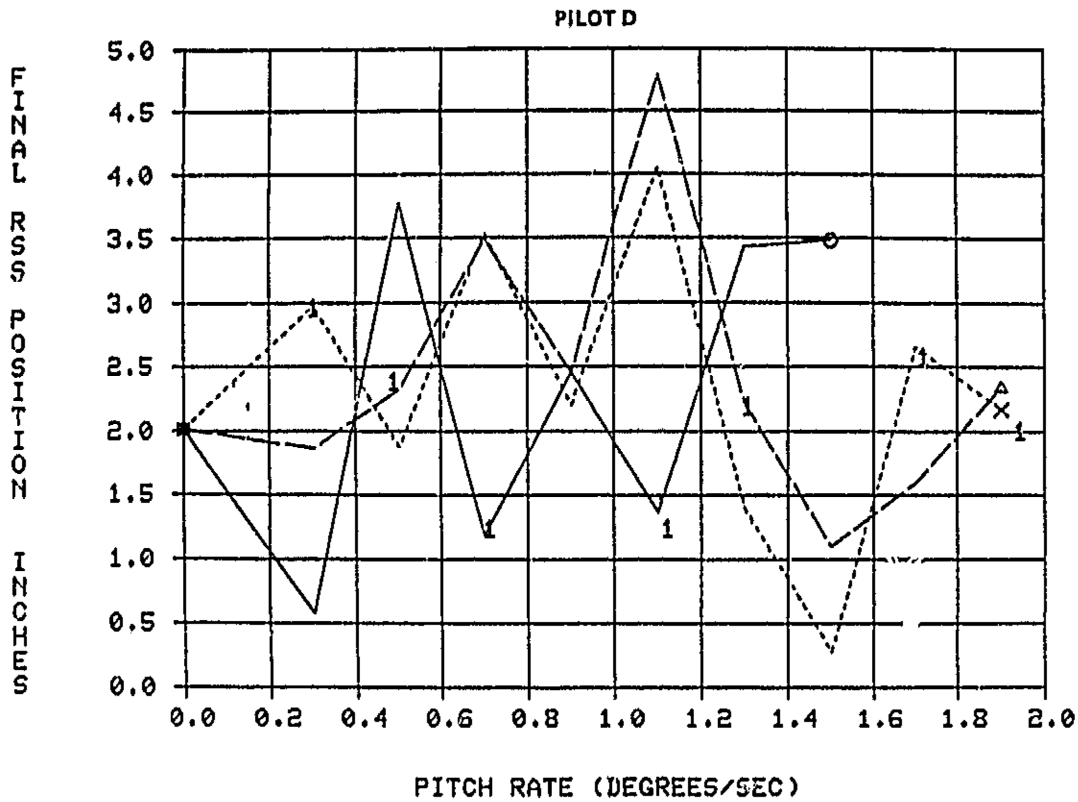

PILOT D
FUEL USED POUNDS
120
110
100
90
80
70
60
50
40
30
20
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

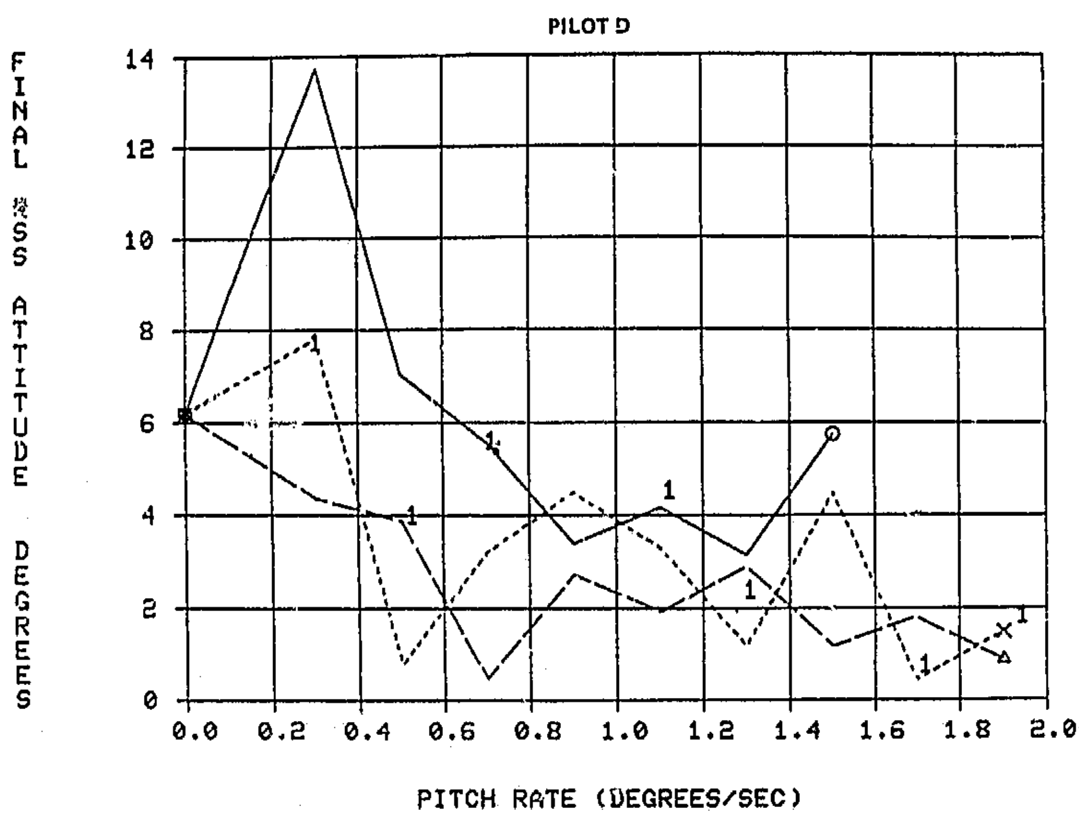

PILOT D
TOTAL # OF FIRINGS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)

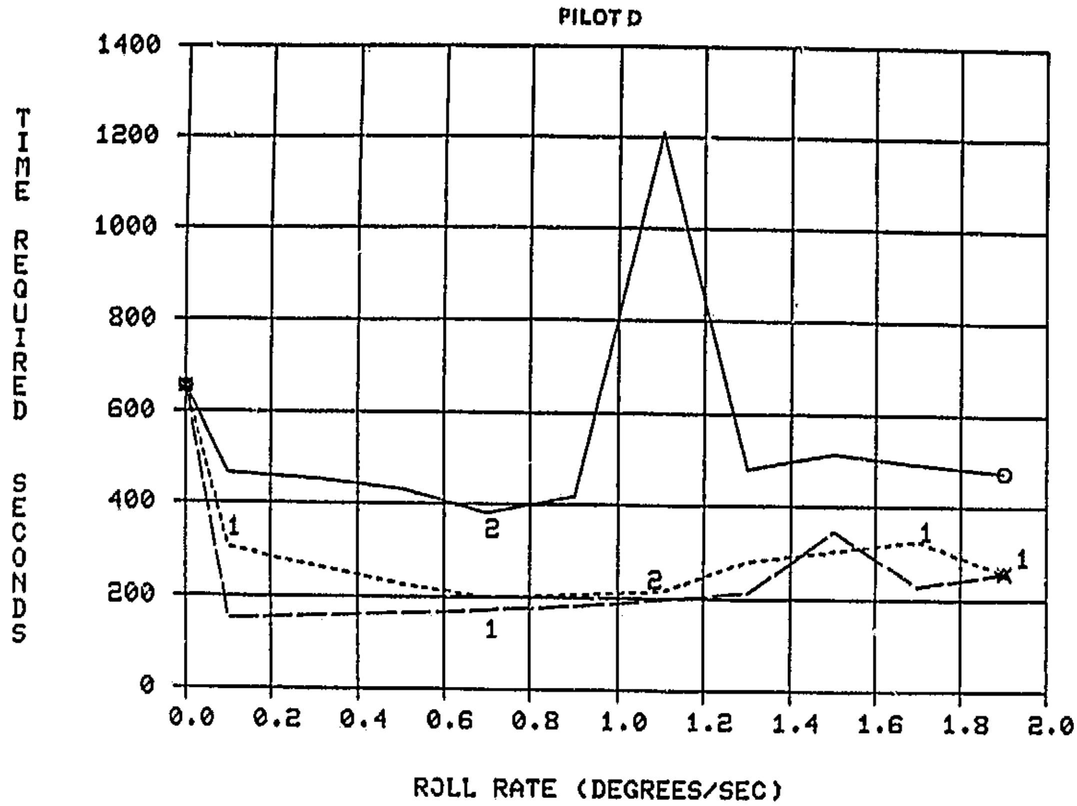

PILOT D
FINAL X VELOCITY FT/SEC
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
PITCH RATE (DEGREES/SEC)

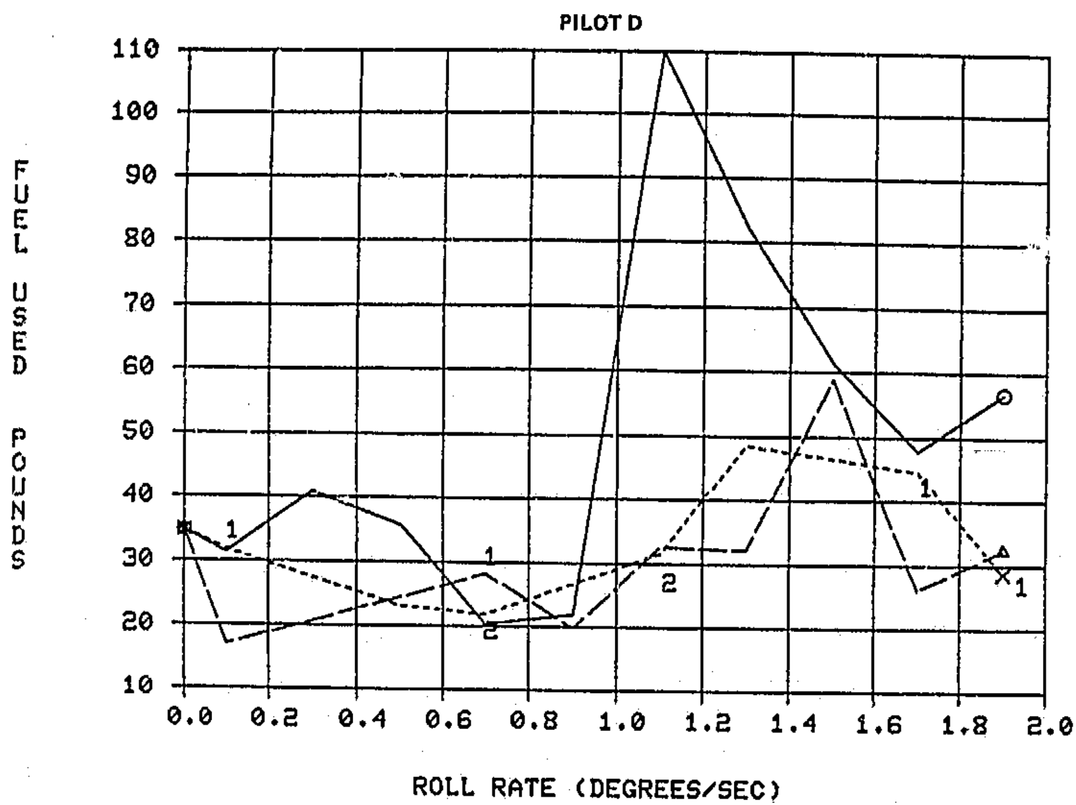

PILOT D
FINAL RSS VELOCITY FT/SEC
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

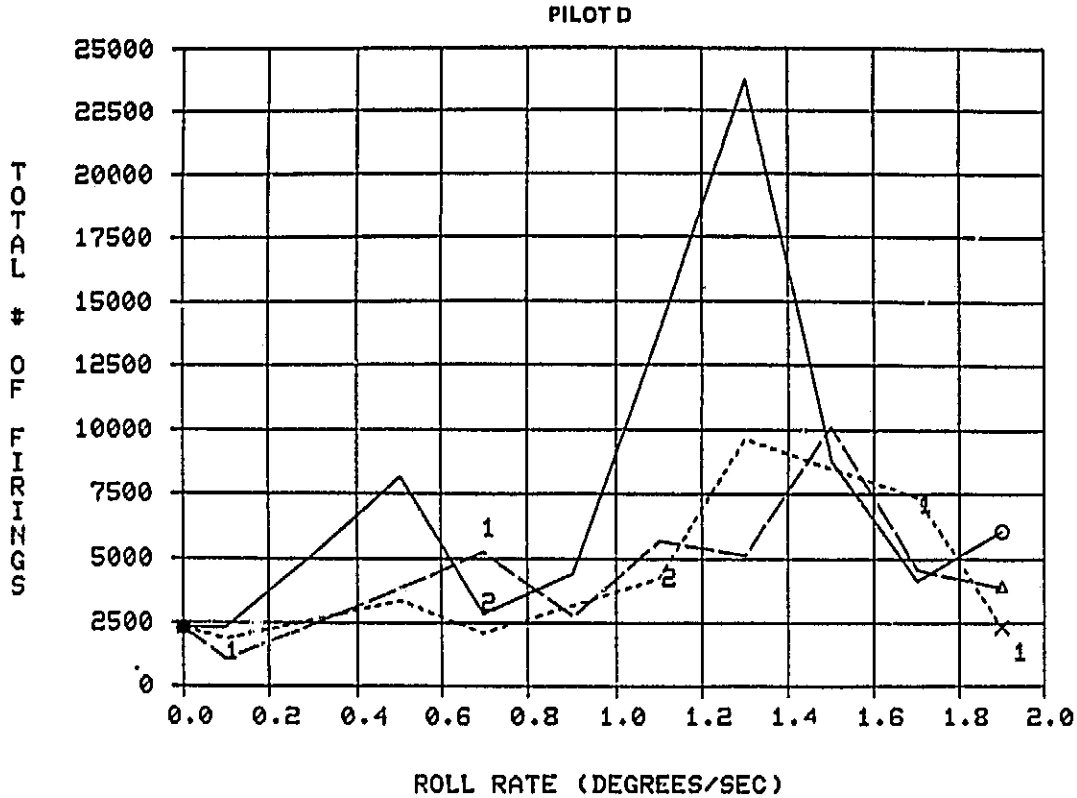

PILOT D
FINAL ROLL ANGLE DEGREES
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

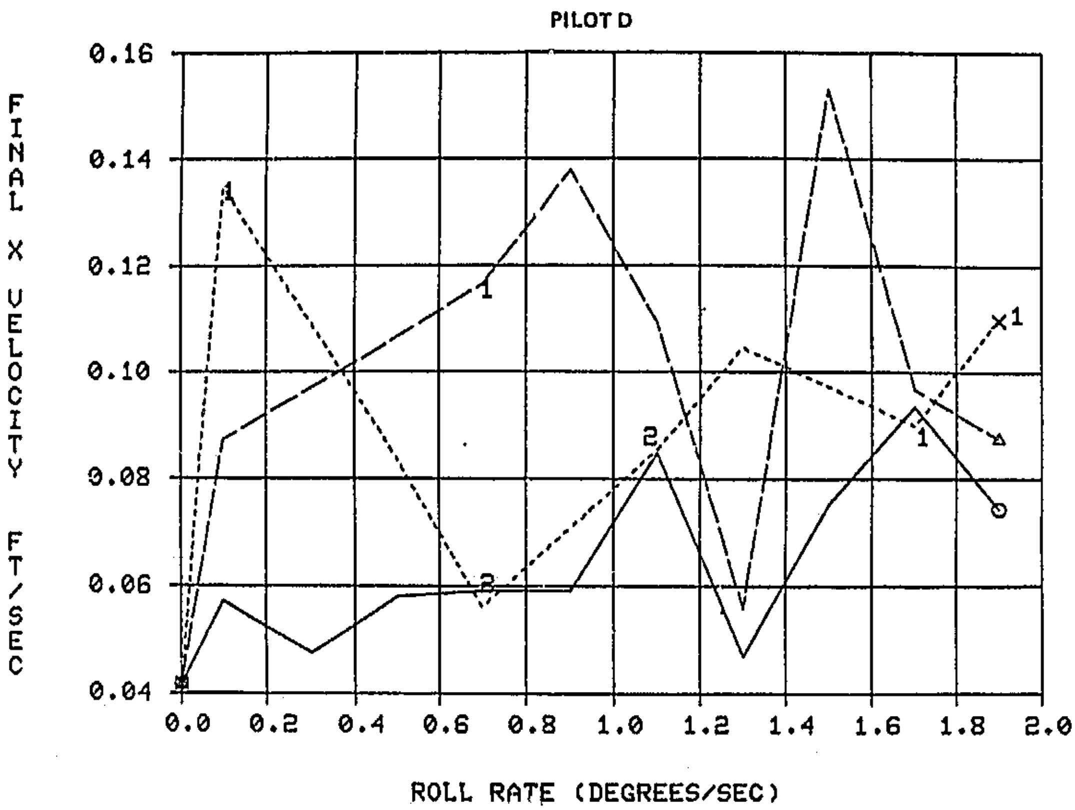

PILOT D
FINAL RSS POSITION INCHES
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

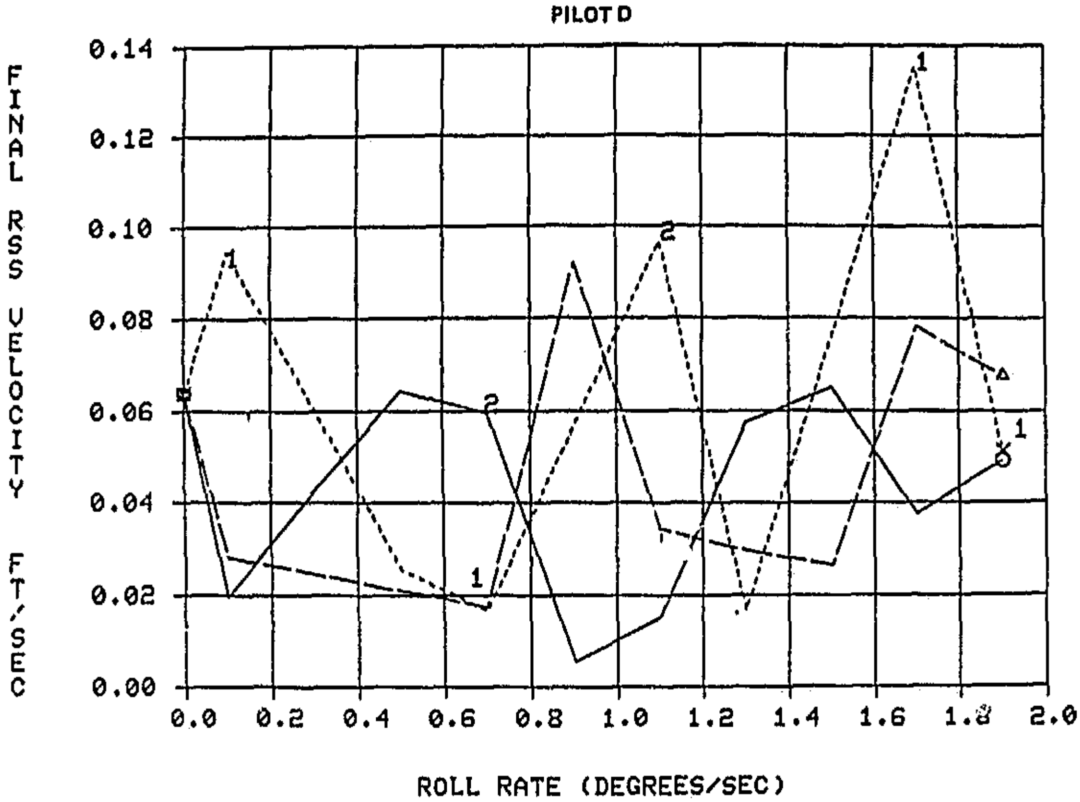

PILOT D
FINAL RSS ATTITUDE DEGREES
14
12
10
8
6
4
2
0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
PITCH RATE (DEGREES/SEC)

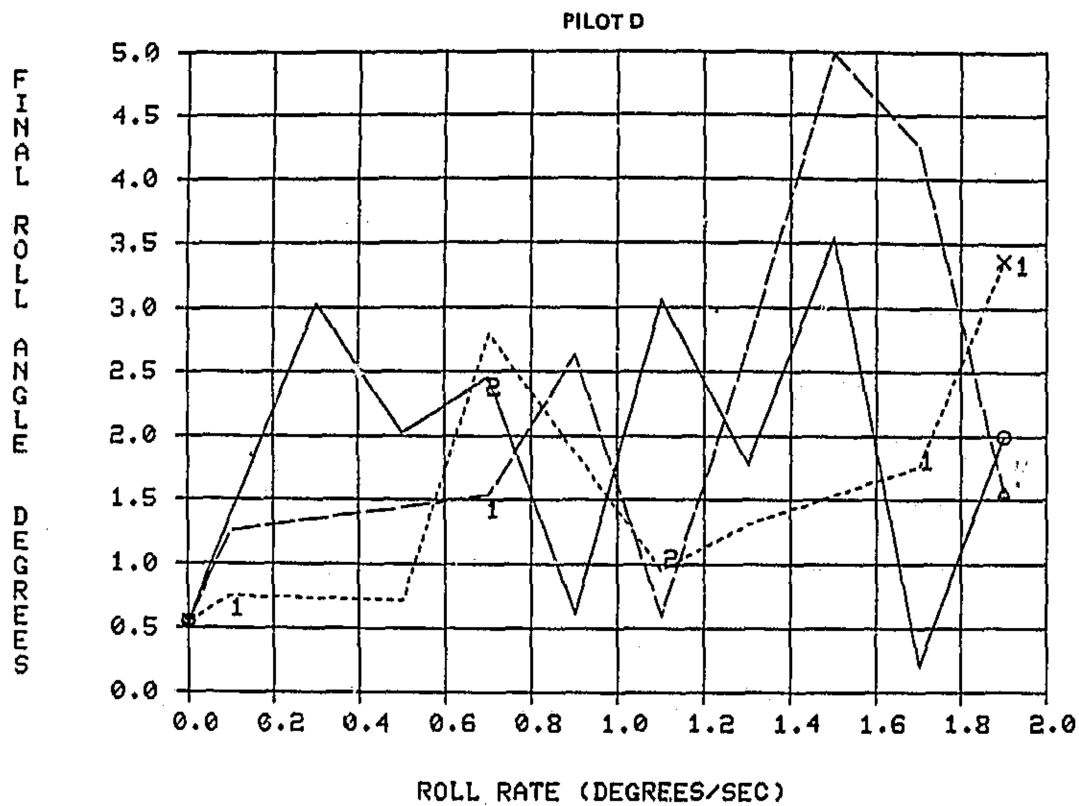

PILOT D
TIME REQUIRED SECONDS
1400
1200
1000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

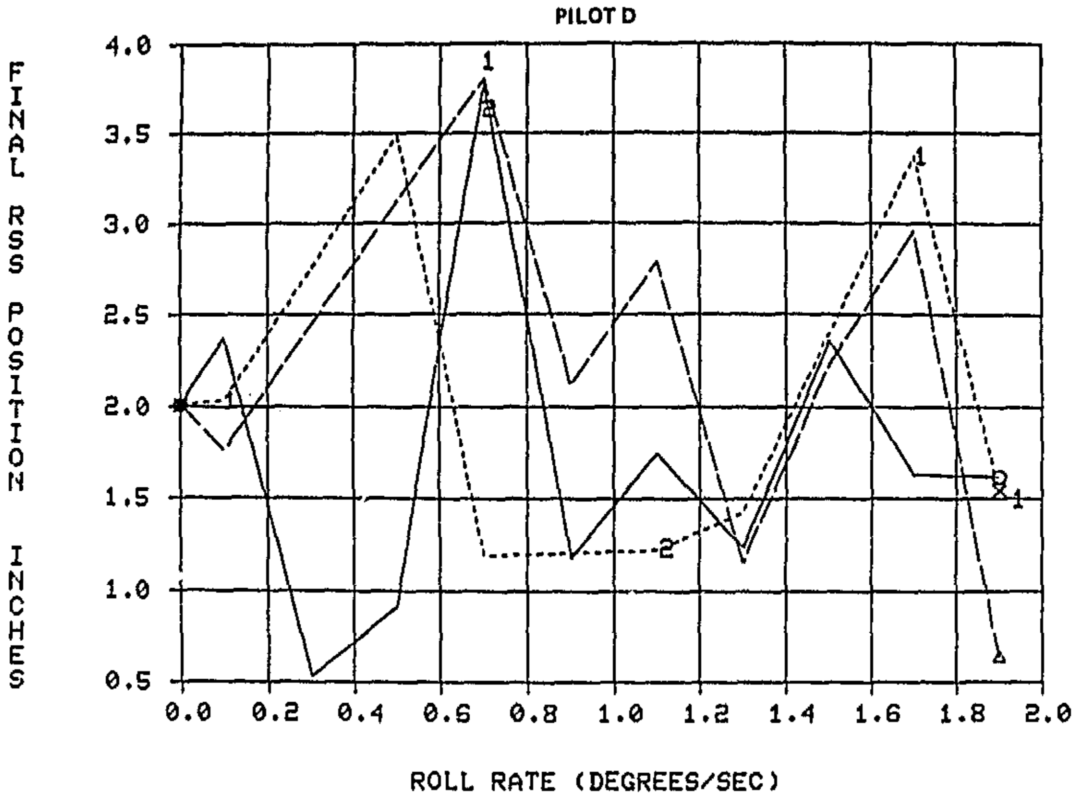

PILOT D
FUEL USED POUNDS
110
100
90
80
70
60
50
40
30
20
10
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)

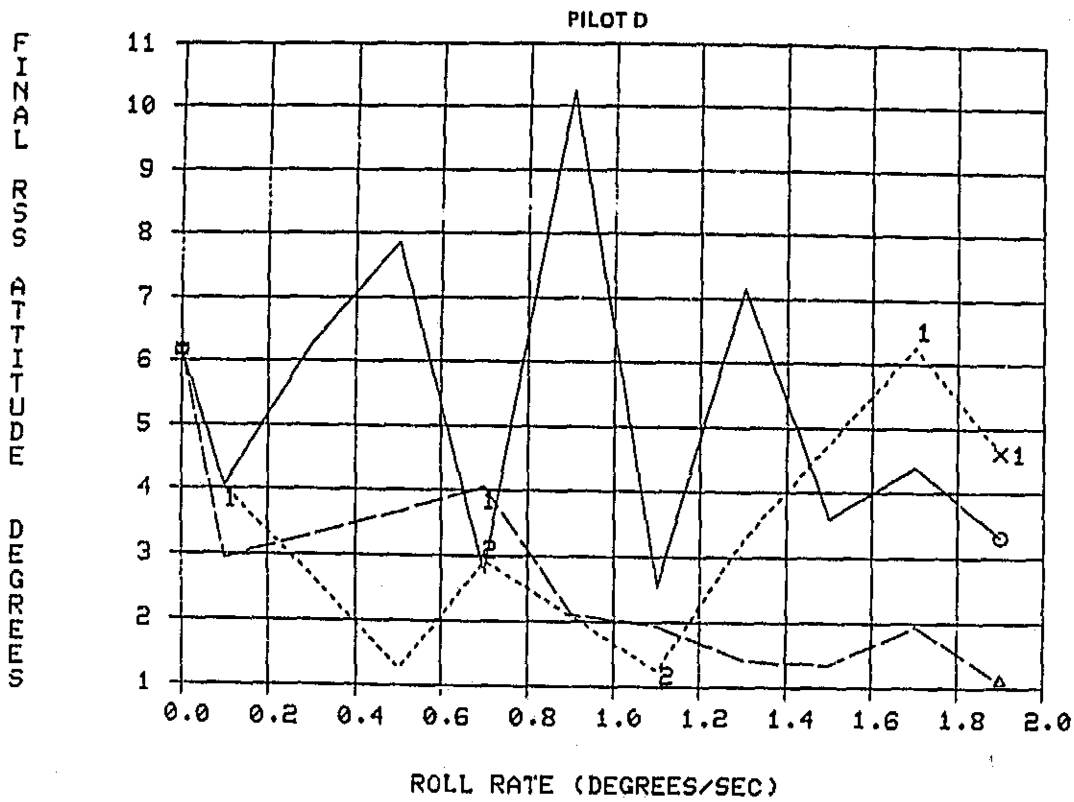

PILOT D
TOTAL # OF FIRINGS
25000
22500
20000
17500
15000
12500
10000
7500
5000
2500
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)


PILOT D
FINAL X VELOCITY FT/SEC
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)


PILOT D
FINAL RSS VELOCITY FT/SEC
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)


PILOT D
FINAL ROLL ANGLE DEGREES
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
ROLL RATE (DEGREES/SEC)


PILOT D
FINAL RSS POSITION INCHES
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)


PILOT D
FINAL RSS ATTITUDE DEGREES
11
10
9
8
7
6
5
4
3
2
1
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
ROLL RATE (DEGREES/SEC)

APPROVAL

DOCKING SIMULATION ANALYSIS OF RANGE DATA REQUIREMENTS FOR THE ORBITAL MANEUVERING VEHICLE

By James D. Micheal and Frank L. Vinz

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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Systems Laboratory

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