FLIGHT EVALUATION OF A KINESTHETICALLY CONTROLLED FLYING VEHICLE

FINAL REPORT

C. E. Satterlee

Integrated Systems Engineering Department
Textron's Bell Aerosystems Company
Buffalo, New York

Report No. 2369-927001
March 1969

Prepared Under Contract NAS 9-8777

for

National Aeronautics and Space Administration
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NASA CR 101937

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FOREWORD

This report presents the results of a flight test evaluation of the handling qualities of small, kinesthetically controlled, rocket powered vehicles in earth gravity and in simulated lunar gravity environment. The work was performed under Contract NAS 9-8777. The period of the program was from August 30, 1967 through March 31, 1968.

The contract was technically supervised by Mr. William Humphrey, Spacecraft Design Office, Manned Spacecraft Center.

Test vehicles, facilities and test direction were provided by the Bell Aerosystems Company.

CONTENTS

ILLUSTRATIONS

TABLES

I. BACKGROUND AND SUMMARY

The feasibility and applicability of flying vehicles in the exploration of the lunar surface has been well established, and a variety of configuration concepts have been developed (References 1 through 5).

These vehicle configurations provided flight control by thrust vectoring, differential throttling, or a combination of both. An alternate control concept is of current interest because it could lead to simplification of the flying vehicle control system.

In this concept, the rocket engines which support the vehicle are rigidly attached to the vehicle, and the pilot leans in the direction in which he wishes to fly. This has been called "kinesthetic," "body motion," or "balance reflex" control by various researchers. This method of control has been demonstrated by the Langley Research Center and others in tethered flight (References 6, 7, and 8) and most recently by Bell Aerosystems in free flight (Reference 9). These tests have provided some evidence that the handling qualities of a kinesthetically controlled vehicle are related to the vehicle rotational inertia.

Whereas successful free flights have been conducted on vehicles of less than 10 slug-ft^2 pitch and roll inertias, recent simulation tests indicated that the inertia range of expected lunar vehicles, from 20 to 150 slug-ft^2, would be unacceptably difficult to control.

The objective of the present contract, reported herein, was to obtain a preliminary evaluation of the handling qualities of a kinesthetically controlled vehicle over a range of inertia from 20 to 130 slug-ft^2 in earth gravity and in simulated lunar gravity and to compare the results with the same vehicles with thrust vector control. In varying the vehicle inertia, an upper limit for flyability was to be sought.

Existing Bell rocket vehicles were modified for kinesthetic control in pitch and roll for earth gravity flights and for simulated lunar flights. The 1-g vehicle in flight is shown in Figures 1 and 2 in its low and high inertia configurations respectively and the 1/6-g vehicle is shown in Figures 3 and 4 in its highest inertia configuration. Jetavators were used for yaw control. Inertia of the vehicles was varied by changing the location of ballast weights.

In earth gravity, the pilot found the vehicle very difficult to fly with kinesthetic control at any inertia tested. The vehicle was easier to control with pivoted thrusters.

Kinesthetic flight in simulated lunar gravity seemed to the pilots to be easier than in earth gravity because of the lower translation acceleration. However, final translation corrections just prior to landing were very difficult to make. Simulated lunar gravity flight was easier with pivoted thruster control than with kinesthetic control.

Moving picture coverage was obtained for all flights.

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Figure 1. 1-g Kinesthetic Vehicle (Low Inertia)

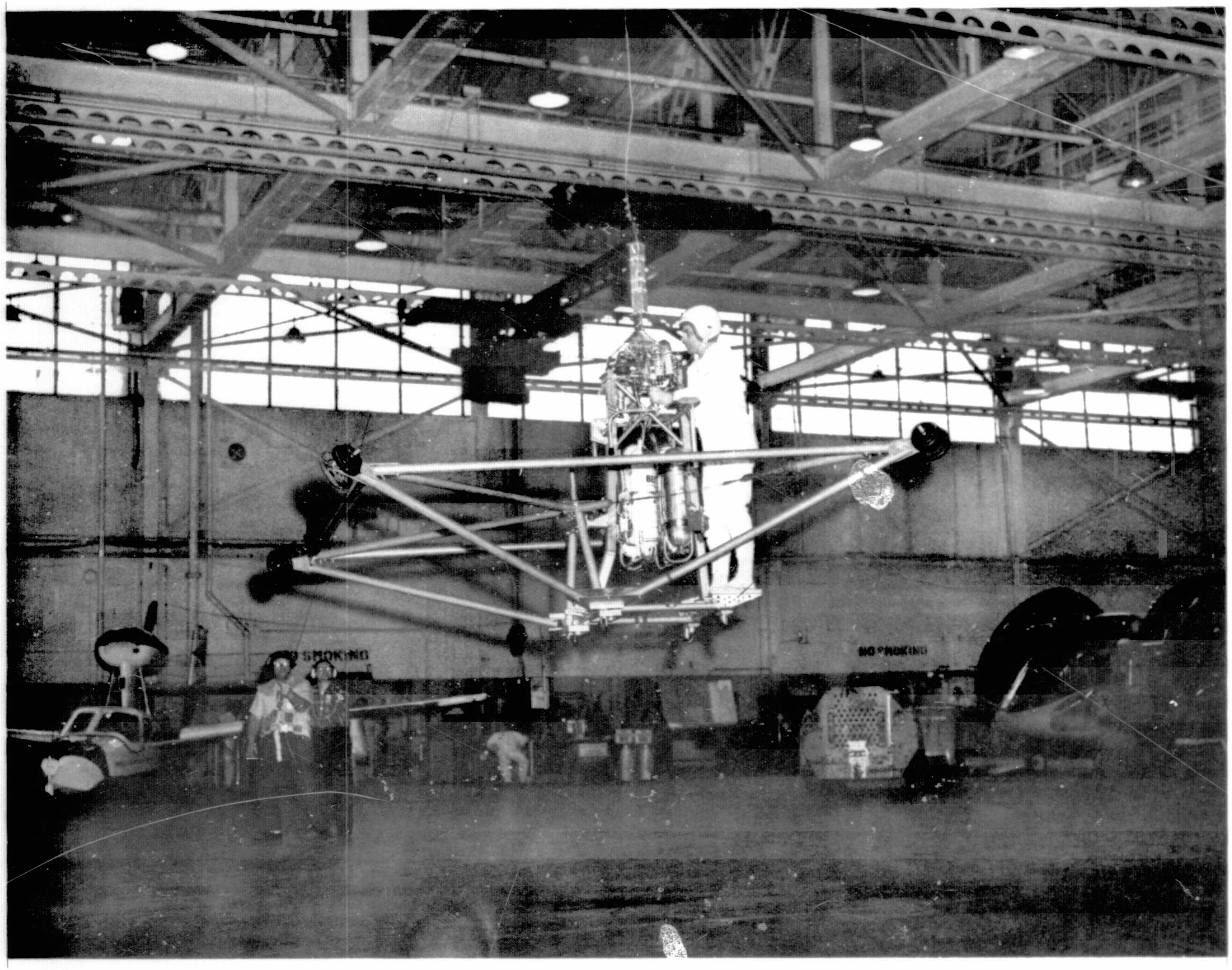

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Figure 2. 1-g Kinesthetic Vehicle (High Inertia)

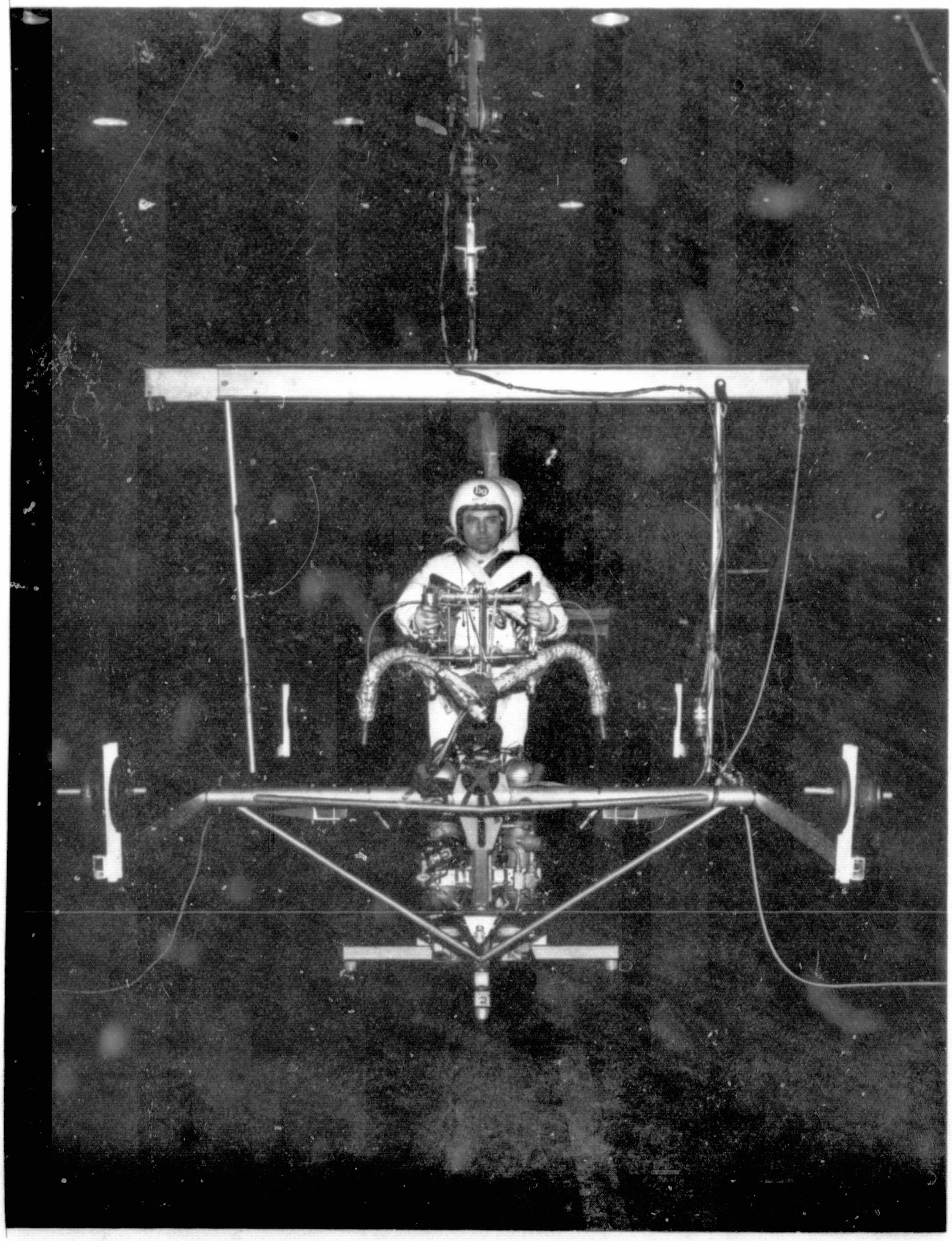

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Figure 3. 1/6-g Kinesthetic Vehicle (High Inertia)

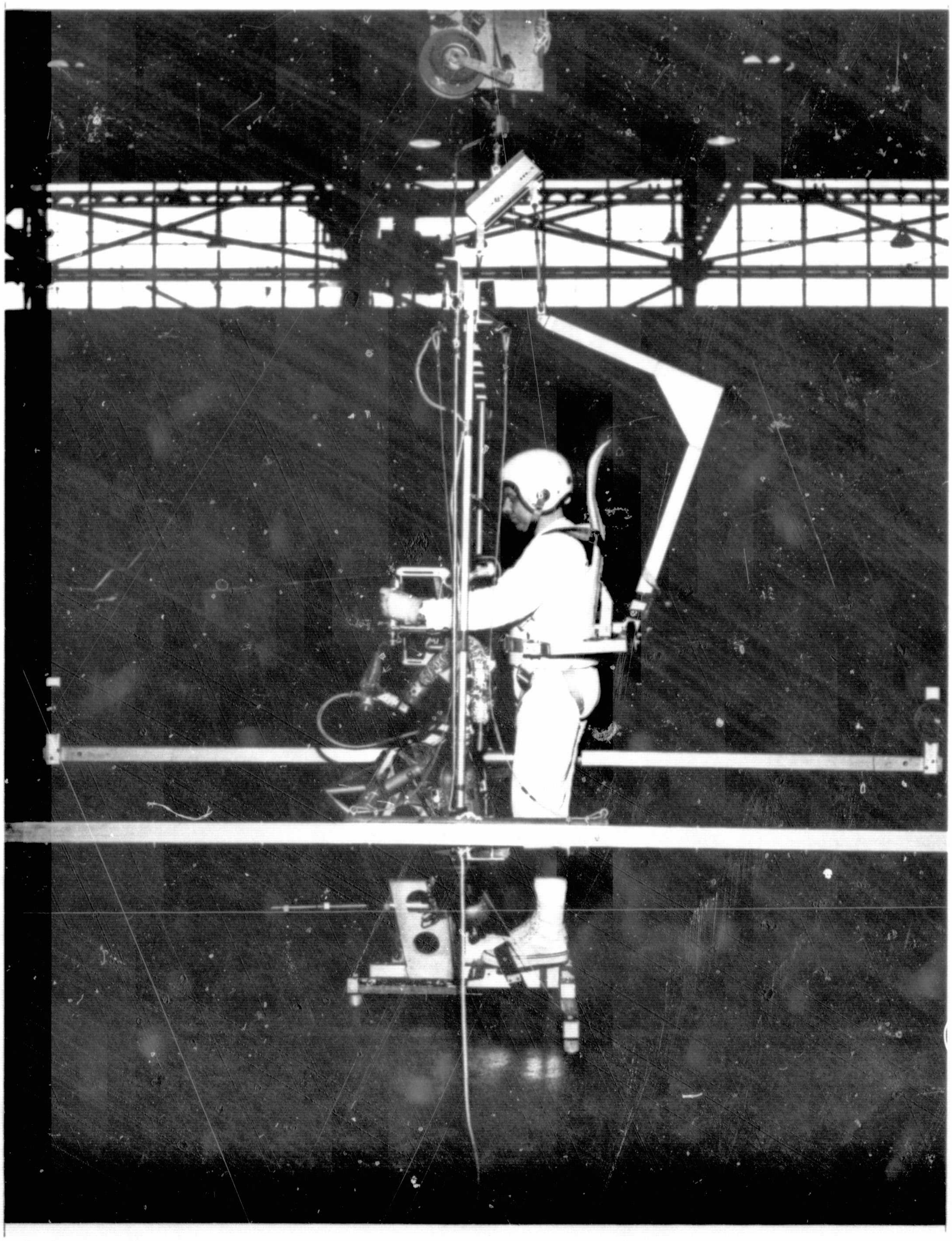

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Figure 4. 1/6-g Kinesthetic Vehicle Suspension System

II. DESCRIPTION OF EQUIPMENT

A. PROPULSION SYSTEMS

Both vehicles are propelled by hydrogen peroxide rocket units that are identical except for the throttle valves, which were designed for different thrust levels.

Each propulsion unit contains propellant tanks, nitrogen pressurant tank, throttle valve, catalytic decomposition chamber and thruster nozzles. The thrust range is determined by the propellant tank pressure which is regulated and adjustable up to 570 psi. Rocket thrust versus throttle setting for each vehicle is shown in Figure 5.

The thruster head assemblies could be pivoted for pitch and roll control or locked in stationary positions for the kinesthetic flights. Yaw control was obtained with the left hand twist grip which actuated ring - jetavators at the thruster nozzle exit planes. Throttle control was obtained by the right hand twist grip.

The propellant load permitted flights up to 20 seconds in earth gravity and up to 40 seconds in simulated lunar gravity.

B. 1-g VEHICLE

The 1-g vehicle was originally designed for free flight with two men. It was modified by adding a vertical ballast support post in the passenger's position on the front of the vehicle. To this was attached a removable outboard frame and ballast weights. Minimum inertia is achieved with the outboard frame removed and with the ballast on the vertical post. Increased inertias are obtained by adding the outboard frame and transferring ballast from the vertical post to the outboard corners of the frame. For kinesthetic control, the thruster heads were locked in a fixed position and the vehicle control handles were moved aft to permit more freedom of body movement. For pivoted thruster flights, the original control handles and pivoting system was reinstalled. Photographs of the kinesthetic configuration are presented in Figures 1 and 2 and a drawing in Figure 6.

Flight safety was provided by an overhead tether system consisting of a 3/16 inch steel cable and pulley-brake system suspended from an overhead trolley. The overhead trolley provided approximately 150 feet of travel. This system permitted free flight with a slack cable over an area of 20 by 150 feet.

C. 1/6-g VEHICLE

The vehicle and its constant tension suspension device used for the flights in simulated lunar gravity (Figure 7) is similar to that used in test flights on the NASA Lunar Landing Research Facility, (Reference 5) except for the following modifications:

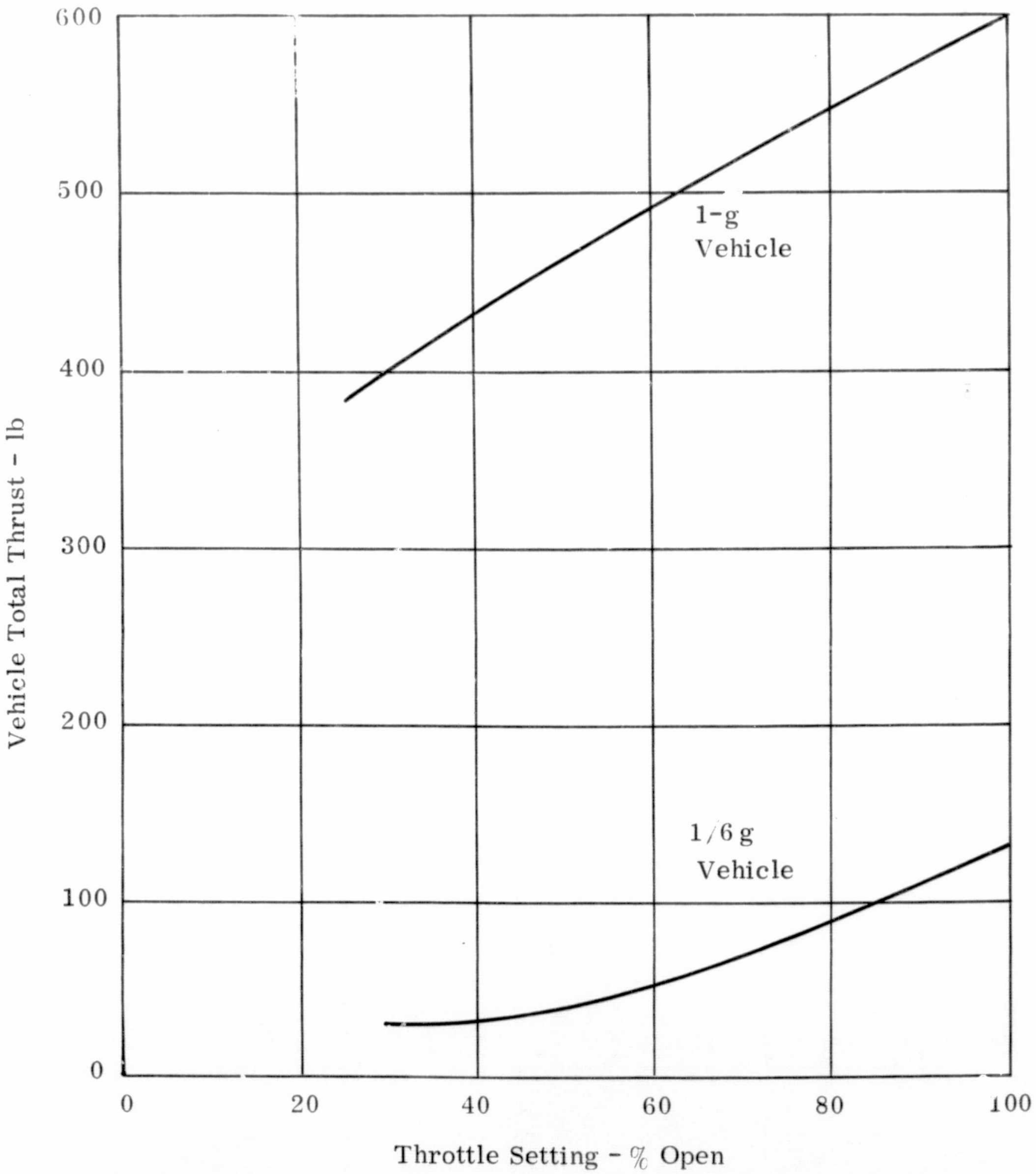
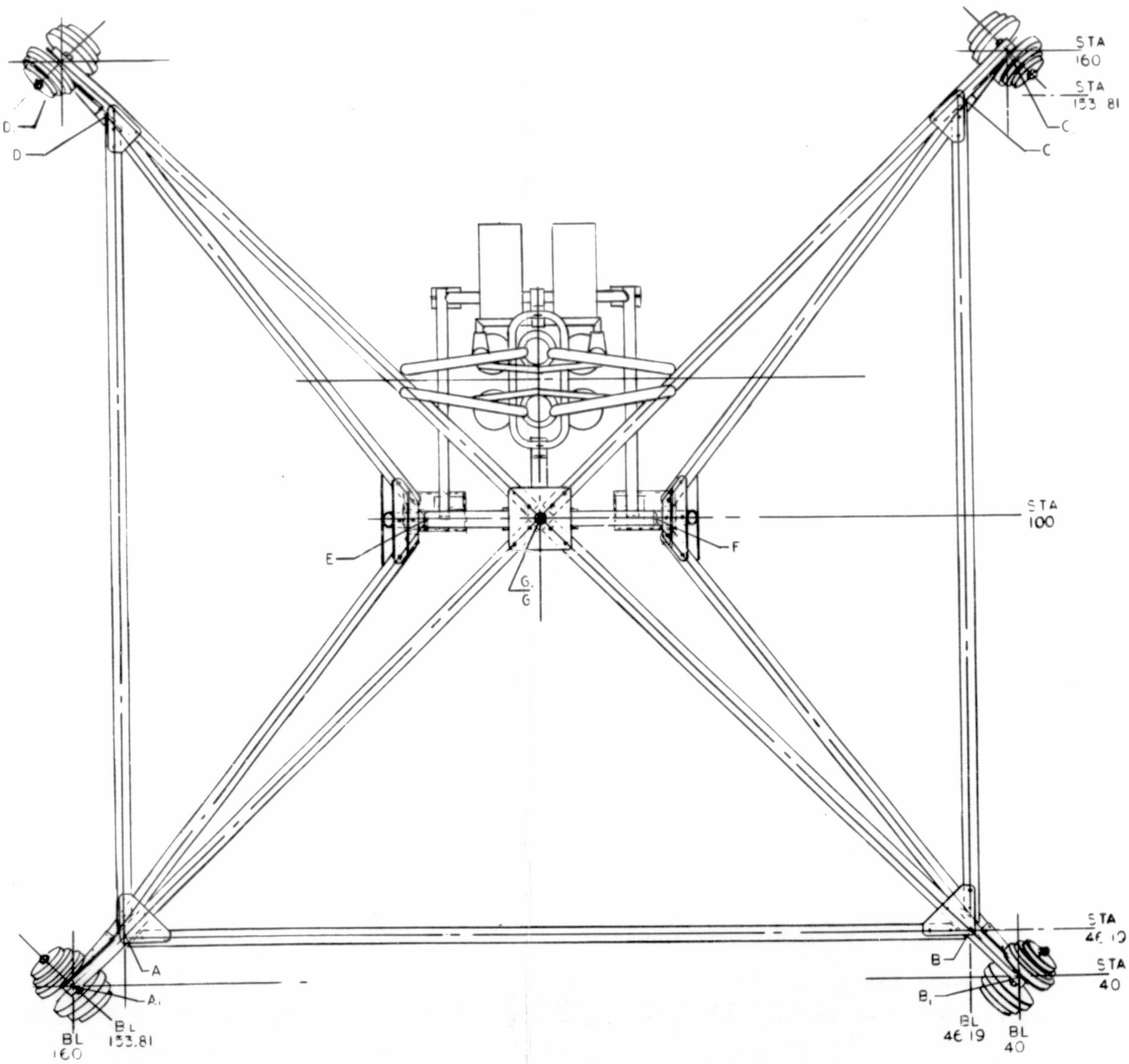


Figure 5. Vehicle Thrust



Report No. 2369-927001

FOLDOUT FRAME #1

TRUE LENGTHS

AB; BC; AD	107.63
AG; BG; CG; DG	76.09
A,A; B,B; C,C; D,D	8.75
G,F; G,E	31.92
A,E; D,E; B,F; C,F	79.30

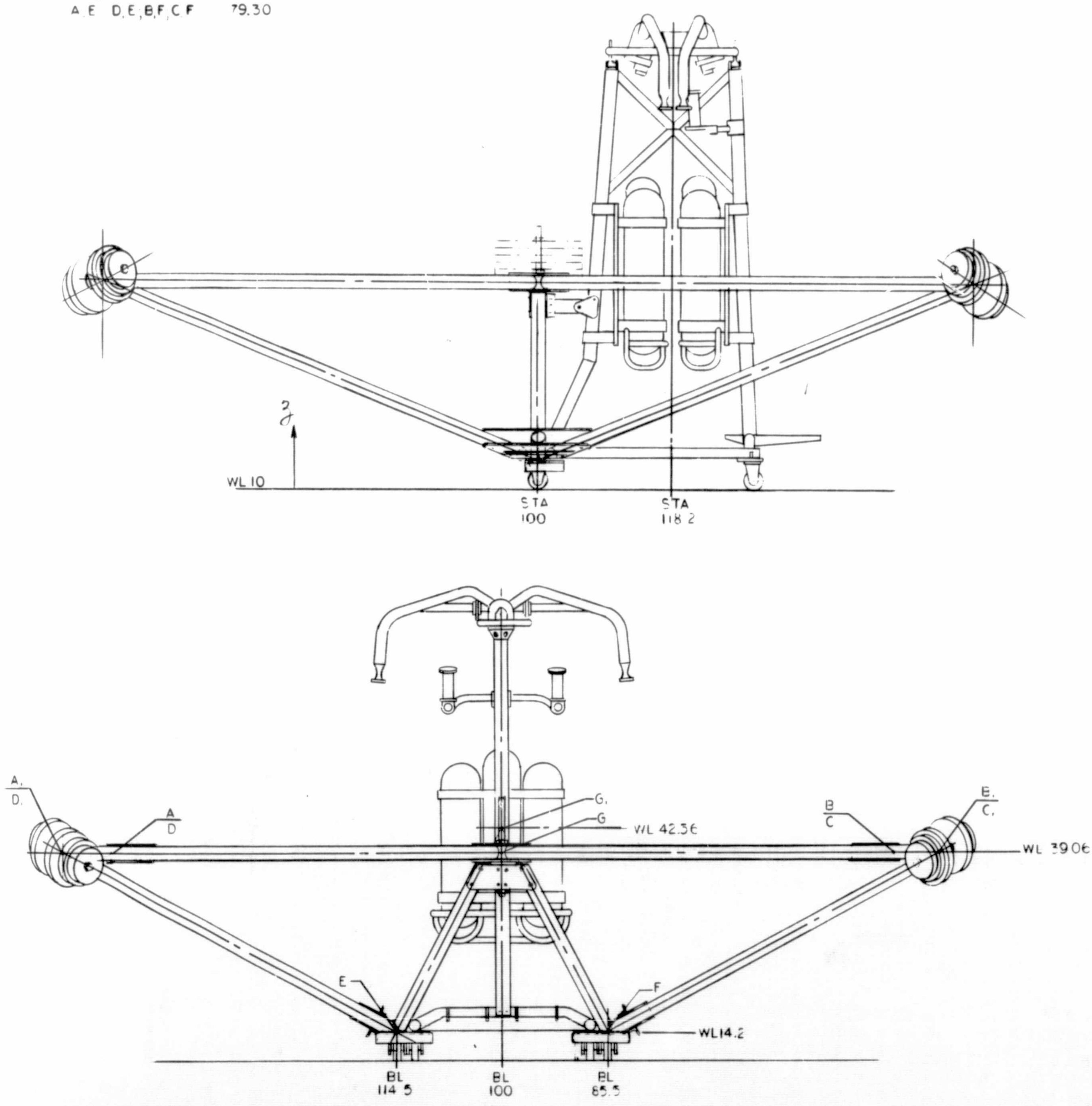


Figure 6. Fixed Thruster Flying Vehicle

FOLDOUT FRAME #2

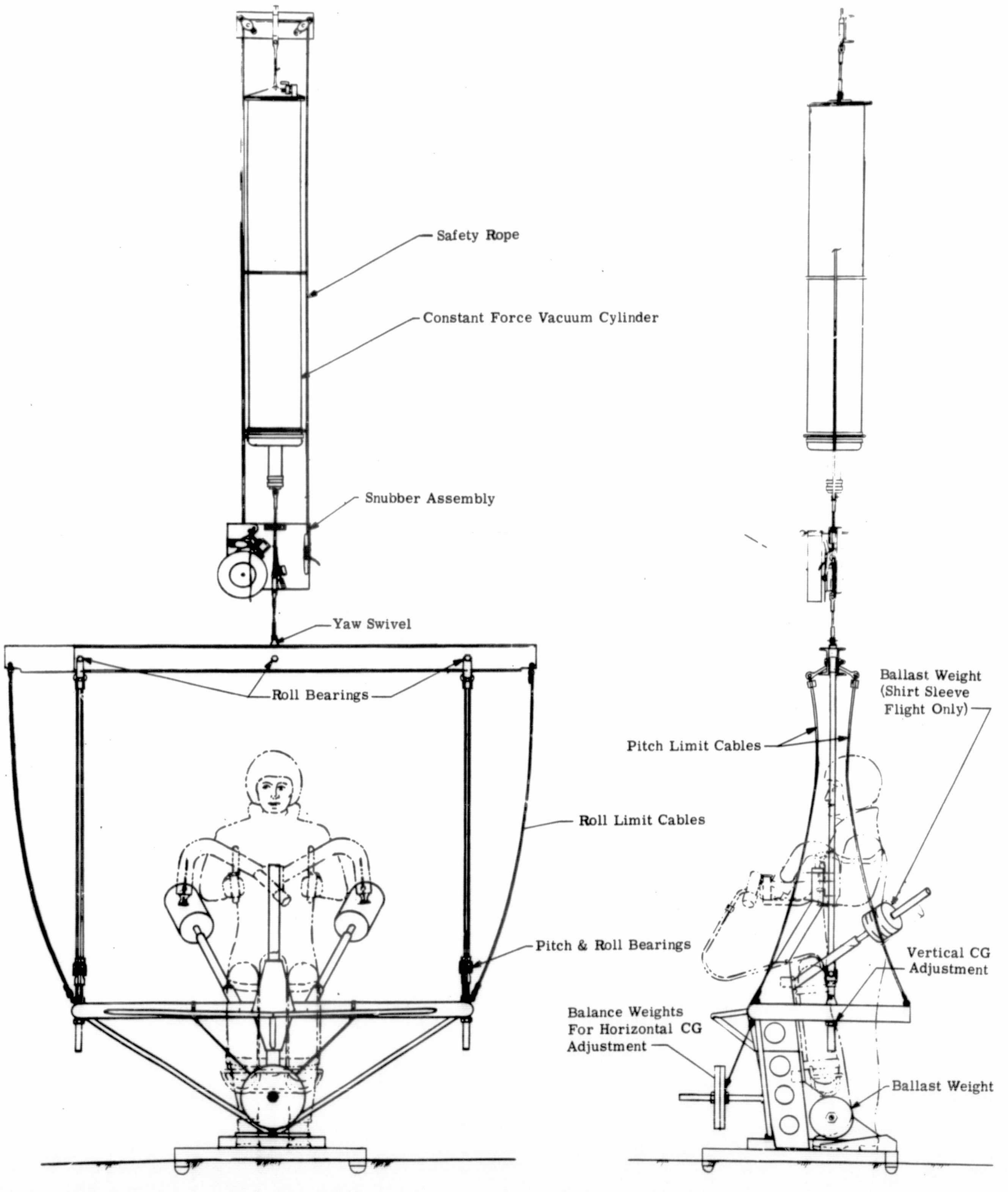


Figure 7. 1/6-g Vehicle Before Modification

(1) The underarm supports were removed.

(2) The thruster head was lowered and locked in position for the kinesthetic flights.

(3) Extension arms were added to the sides of the vehicle so that ballast could be moved outboard to increase the vehicle inertia.

(4) An independent pilot suspension system was added.

The modified vehicle and pilot suspension is shown in Figures 3 and 4. The vehicle and pilot are suspended from a constant force vacuum cylinder designed to support 5/6 of the flight weight to simulate flight in lunar gravity. The method used to support 5/6 of the pilot's weight for proper simulation of lunar kinesthetic control power is shown in Figure 4.

The main support cable provides a constant upward force equal to 5/6 of the total system weight. The cable is attached to a pivoting bar, which supports the vehicle at one end and the pilot at the other. The ratio of the arm lengths is such that 5/6 of the vehicle weight balances 5/6 of the pilot's weight. The vehicle is supported at its center of gravity in a two-axis gimbal. The operator suspension supports the operator at his center of gravity in a two-axis gimbal. The main support cable supports the entire system at the system center of gravity. This arrangement is based on the control inputs being generated by the pilot moving as a rigid body so that his center of gravity remains fixed relative to his support harness pitch and roll axes.

The entire system is suspended from a low friction trolley on an overhead rail that permits 100 feet of travel. The constant tension vacuum cylinder permits 10 feet of vertical travel. A snubber assembly is provided for safety, and can be actuated by the pilot or by a ground observer. Instrumentation provides vehicle pitch and roll attitude, throttle and yaw control position, vertical and downrange position, and vacuum cylinder force versus time.

III. WEIGHT, INERTIA AND CONTROL CHARACTERISTICS

A. 1-g VEHICLE

A weight summary for the 1-g vehicle is shown in Table I. The vehicle c.g., location and moments of inertia (less pilot) about the vehicle c.g., are shown in Table II. The moments of inertia in pitch and roll were obtained by swinging the vehicle and the yaw inertia was calculated.

The control sensitivities were calculated for pitch and roll, with kinesthetic control and with pivoted thrusters, for the three basic inertia configurations with and without propellant. These are shown in Table III. The kinesthetic control sensitivity is expressed in degrees per second squared per inch of pilot c.g. movement, while the pivoted thruster sensitivity is expressed in degrees per second squared per degree of thruster motion. The inertias used to calculate control sensitivity are those from Table II adjusted to include the pilot. This increment is approximately 38 slug-ft^2 in pitch and 22 slug-ft^2 in roll. The sensitivities are at a thrust-to-weight ratio of 1.0.

The control sensitivities in yaw are not shown since the jetavator characteristics were not measured. Flights were primarily straight with yaw control being used only to maintain the original heading.

B. 1/6-g VEHICLE

A weight summary for the 1/6-g vehicle is shown in Table IV. The vehicle moments of inertia about the vehicle center of gravity are shown in Table V. The moment of inertia in pitch was measured by swinging the vehicle. The moments of inertia in roll and yaw were calculated. Control sensitivities for kinesthetic and pivoted thruster control are presented in Table VI.

Geometrical factors which affect the simulation characteristics are discussed under the section entitled "Evaluation of Simulation Fidelity." These effects decrease the control power and essentially change the control characteristics to those of a vehicle of higher inertia. This effect has been taken into account in calculating the kinesthetic control sensitivities presented in Table VI. The control sensitivity in yaw was not calculated. The inertias used to calculate control sensitivities are those in Table V corrected for the addition of the pilot. The increments for this were 18 slug-ft^2 in pitch and 20 slug-ft^2 in roll.

TABLE I

1g VEHICLE MASS SUMMARY

	Mass	
	lb	kg
Vehicle Structure	147.0	66.7
Crushable Honeycomb (Safety Tether)	5.7	2.6
Ballast Frame	68.0	30.8
Ballast*	100.0	45.4
Empty Weight	320.7	145.5
Nitrogen Pressurant	4.0	1.8
Hydrogen Peroxide Propellant	94.0	42.6
Pilot and Pilot Gear	180.0	81.6
Gross Weight	598.7	271.6

* When the ballast frame is removed it is replaced by equivalent ballast on the center post of the vehicle in order to preserve vehicle c.g. position

TABLE II

1g VEHICLE MOMENTS OF INERTIA (LESS PILOT)

Slug-ft^2 (kg-m^2)

	Inboard Ballast without Frame	Inboard Ballast with Frame	Outboard Ballast with Frame
Pitch - Tanks Full	23.6 (32.0)	47.3 (64.1)	130.1 (176.4)
Pitch - Tanks Empty	19.5 (26.4)	43.2 (58.6)	126.0 (170.9)
Roll - Tanks Full	15.3 (20.7)	38.9 (52.7)	124.0 (168.1)
Roll - Tanks Empty	13.7 (18.6)	37.3 (50.6)	122.4 (166.0)
Yaw - Tanks Full	8.0 (10.1)	36.7 (49.8)	201.3 (273.0)
Yaw - Tanks Empty	6.9 (9.4)	35.6 (48.3)	200.2 (271.5)

Center of Gravity Location
in (m)

	Tank Empty	Tank Full
Water Line	40.2 (1.02)	40.2 (1.02)
Body Station	106.5 (2.71)	109.2 (2.77)

TABLE III

1-g VEHICLE CONTROL SENSITIVITY

Kinesthetic - $deg/sec^2/in.$ ($deg/sec^2/m$)

	Inboard Ballast Without Frame		Inboard Ballast With Frame		Outboard Ballast With Frame	
Pitch - Tanks Full	14.1	(0.36)	10.1	(0.26)	5.1	(0.13)
Pitch - Tanks Empty	15.1	(0.38)	10.5	(0.27)	5.2	(0.13)
Roll - Tanks Full	23.2	(0.59)	14.2	(0.36)	5.9	(0.15)
Roll - Tanks Empty	23.6	(0.60)	14.3	(0.36)	5.9	(0.15)

Pivoted Thrusters - $deg/sec^2/deg$

	Inboard Ballast Without Frame	Inboard Ballast With Frame	Outboard Ballast With Frame
Pitch - Tanks Full	17.1	12.2	6.2
Pitch - Tanks Empty	19.0	13.3	6.6
Roll - Tanks Full	27.0	17.2	7.2
Roll - Tanks Empty	29.7	18.0	7.4

TABLE IV

1/6 g VEHICLE MASS SUMMARY

	Mass lb	Mass kg
Vehicle Structure	170.8	77.5
Pitch Beam	4.0	1.8
Ballast	162.4	73.7
Vehicle Weight in Pitch	337.2	153.0
Roll Beam	66.7	30.3
Vehicle Weight in Roll	403.9	183.3
Pilot and Pilot Gear	190.0	86.2
Pilot Suspension	30.0	13.6
Gross Weight Dry	623.9	283.1
Nitrogen Pressurant	2.0	0.9
Hydrogen Peroxide Propellant	47.0	21.3
Gross Weight Wet	672.9	305.3

TABLE V

1/6-g VEHICLE MOMENTS OF INERTIA (LESS PILOT)

Slug ft^2 (kg m^2)

			Minimum	Maximum
Pitch	-	Tanks Empty	38.7 (52.5)	156.8 (212.6)
Pitch	-	Tanks Full	39.7 (53.8)	157.8 (214.0)
Roll	-	Tanks Empty	67.8 (91.9)	77.1 (104.5)
Roll	-	Tanks Full	68.9 (93.4)	78.2 (106.0)
Yaw	-	Tanks Empty	55.8 (75.7)	227.1 (307.9)
Yaw	-	Tanks Full	56.1 (76.1)	227.4 (308.4)

TABLE VI

1/6 g VEHICLE CONTROL SENSITIVITY

Kinesthetic Control - deg/sec^2/in. (deg/sec^2/m)

	Minimum Inertia	Maximum Inertia
Pitch - Tanks Empty	2.12 (0.54)	0.68 (0.17)
Pitch - Tanks Full	2.06 (0.52)	0.68 (0.17)
Roll - Tanks Empty	2.37 (0.60)	2.14 (0.54)
Roll - Tanks Full	2.30 (0.58)	2.08 (0.53)

Pivoted Thrusters - deg/sec^2/deg

	Minimum Inertia	Maximum Inertia
Pitch - Tanks Empty	1.76	0.44
Pitch - Tanks Full	2.86	0.72
Roll - Tanks Empty	0.92	0.81
Roll - Tanks Full	1.51	1.33

IV. FLIGHT TEST PLAN AND RESULTS

A. FLIGHT TEST PLAN

The flight tests consisted of a series of 26 flights in earth gravity and a series of 15 flights in simulated lunar gravity. Kinesthetic and pivoted thruster control were used for comparison. The plan started with low inertia configurations and the inertia was increased as the flights progressed. The test plan is summarized in Table VII. Modifications to the vehicle were made as required as the flights progressed.

B. BACKGROUND

Two pilots were used for the evaluations. Pilot A had previously flown over 700 flights with pivoted thrusters in the test vehicles and other similar vehicles in both earth gravity and simulated lunar gravity. He had also flown 20 flights in earth gravity and eight flights in simulated lunar gravity with kinesthetic control. Pilot B had previously flown 29 flights in earth gravity and three flights in simulated lunar gravity with kinesthetic control and five flights in simulated lunar gravity with pivoted thruster control. Both pilots had previously flown, with kinesthetic control, a vehicle that had an inertia of about six slug-ft^2. Both pilots found it quite easy to fly (See Reference 9).

Evaluations were made by flight observers and obtaining pilot's comments. In addition, on the 1/6-g flights, time histories were obtained of pitch and roll attitude, downrange distance, altitude, and throttle and yaw controller position. The data tapes are presented in Appendix B of this report.

Moving picture coverage of all flights was provided.

C. EARTH GRAVITY FLIGHT RESULTS

These flights were flown with the vehicle shown in Figure 6, and the flight sequence tabulated in Table VII. A "flight" is the expenditure of one tank load of propellant, which provides approximately 20 seconds flight duration. On earlier flights, two or three short hops were accomplished with each tank load of propellant, and are listed as one "flight". As the program progressed, flight duration increased until near the end, almost the entire propellant load was expended in one flight.

Initial flights of this vehicle, using kinesthetic control, disclosed that the vehicle was extremely difficult to stabilize, and impossible to maneuver.

In order to ascertain that the difficulties in stability and control were not due to some hidden defect in the propulsion system, the vehicle was temporarily converted to a pivoted thruster configuration and a successful check flight made. During this flight stabilization and control were satisfactory, which indicated that the problems being encountered were inherent in the kinesthetic control method being employed.

TABLE VII

TEST FLIGHT SEQUENCE

Flight Condition	Control Mode*	Vehicle Inertia slug - ft^2	Number of Flights Pilot A	Pilot B
lg	K	23.6	8	7
	K	47.3	4	0
	K	130.1	2	1
	P	130.1	3	1
1/6 g	K	39.0	2	2
	K	50.0	3	0
	K	157.0	4	2
	P	157.0	2	0

*K - Kinesthetic

P - Pivoted Thrusters

As the program progressed, modifications were made to the vehicle, to the safety tether system, and to the flight procedures, in order to improve stability and control. In addition, vehicle inertia was increased in steps. Despite the changes made during the tests, and the improvement due to pilot learning, it is possible to discern the effect on handling qualities of the increase in vehicle inertia. The specific changes from flight to flight are tabulated in Appendix A and the effects are discussed below.

1. Effect of Vehicle Inertia

In order to describe the effect of increased vehicle inertia, a distinction should be made between ease of stabilization, as measured by ability to hover, and ease of control, as measured by ability to maneuver the vehicle to a predetermined spot, come to a stop, and land.

At the lowest vehicle inertia (23.6 slug ft^2 in pitch), the vehicle was extremely difficult to stabilize. Both pilots found that they could hold the vehicle in a stable attitude for only a few seconds. If they were not at the proper trim position at lift off, or if they induced a horizontal velocity, it was almost impossible to bring the vehicle to a stop before running to the limit of the safety tether system. To observers, the flights generally looked better than they felt to the pilot. Both pilots felt that they were not in control of the vehicle on many of the flights. In the first few seconds the pilot either effected a landing as he felt the vehicle going out of control, or the safety tether man aborted the mission because the vehicle was exceeding the safety tether limits. Based on the test conditions (short flight time, etc.), Pilot A gave an overall vehicle rating of 10. The pilot rating scale is reproduced in Figure 8 for reference.

The vehicle inertia was increased to 47.3 slug ft^2. Pilot A made four flights at this inertia. Vehicle angular motions and resulting translation acceleration developed noticeably slower. The pilot found the vehicle easier to hover, but still unsatisfactory in regard to ability to maneuver. When vehicle inertia was increased to 130.1 slug ft^2, its angular acceleration became slow enough so that the pilots had time to think about the proper control inputs, and could hover the vehicle more easily than at the lower inertia. However, maneuvering control to a specified spot was still difficult. Final translation corrections prior to landing, which were difficult to make at low inertia, were also difficult to make at high inertia. Pilot A provided the following ratings for the highest inertia condition:

Pitch - 5
Roll - 7
Yaw - 8

It should be noted that yaw was not controlled kinesthetically, and the poor pilot rating was due to the very low control power provided.

In summary, the ability to hover appeared to improve with increasing inertia, within the range tested. The ability to maneuver to a precise touchdown did not improve. At no inertia was the flying ability considered acceptable. Neither pilot had any confidence in his ability to make a satisfactorily controlled flight from one point to another. They did

<table>
<tr><td rowspan="9">Controllable

Capable of being Controlled or Managed in Context of the Task or Flight Phase, with Available Pilot Attention</td><td rowspan="6">Acceptable to Pilot

*Pilot Compensation if Required to Achieve Acceptable Performance in Task is Feasible
*May have Deficiencies for which Pilot desires Improvement, but Adequate for Task or Flight Phase</td><td rowspan="3">Satisfactory to Pilot

*Meets all Demands and Expectations
*Clearly Adequate for the Task or Flight Phase
*Good Enough without Improvement</td><td>*Excellent, Highly Desirable</td><td>1</td></tr>
<tr><td>*Good, Pleasant, Well Behaved</td><td>2</td></tr>
<tr><td>*Fair, some mildly Unpleasant Characteristics
*Good Enough for Task or Flight Phase without Improvement</td><td>3</td></tr>
<tr><td rowspan="3">Unsatisfactory to Pilot

*Reluctantly Acceptable
*Deficiencies which Warrant Improvement
*Performance Adequate for Task or Flight Phase with Feasible Pilot Compensation</td><td>*Some Minor but Annoying Deficiencies
*Effect on Performance is easily Compensated for by Pilot
*Improvement is Requested</td><td>4</td></tr>
<tr><td>*Moderately Objectionable Deficiencies
*Reasonable Performance requires Considerable Pilot Compensation
*Improvement is Needed</td><td>5</td></tr>
<tr><td>*Very Objectionable Deficiencies?
*Require best Available Pilot Compensation to Achieve Acceptable Performance
*Major Improvements are Needed</td><td>6</td></tr>
<tr><td rowspan="3">Unacceptable to Pilot

*Deficiencies which require Mandatory Improvement
*Inadequate Performance for Task or Flight Phase even with Maximum Feasible Pilot Compensation</td><td rowspan="3"></td><td>*Major Deficiencies but Controllable
*Performance Inadequate or Pilot Compensation Required for Minimum Acceptable Performance in Task or Flight Phase is too High
*Requires Mandatory Improvement for Acceptance</td><td>7</td></tr>
<tr><td>*Controllable with Difficulty in Task and Flight Phase
*Requires Substantial Pilot Skill to Retain Control and Continue Mission</td><td>8</td></tr>
<tr><td>*Marginally Controllable in Task or Flight Phase
*Requires Maximum Available Pilot Skill to Retain Control</td><td>9</td></tr>
<tr><td colspan="3">Uncontrollable

*Control will be Lost during some Portion of Task and Flight Phase</td><td>*Uncontrollable in Task or Flight Phase</td><td>10</td></tr>
</table>

Figure 8. Pilot Rating Scale

feel that a flight time of minutes rather than seconds would make the task of learning to fly the vehicle much easier.

At the conclusion of the kinesthetically controlled flights, the rocket and control pivots were unlocked, and four thrust vector controlled flights made, with a vehicle pitch inertia of 130.1 slug-ft^2. The flights were considerably improved over those with kinesthetic control. Even on his first flight, each pilot was able to control the vehicle for the full flight duration. Pilot A gave ratings of:

Pitch - 4
Roll - 3 1/2
Yaw - 3
Overall Vehicle - 4

Pilot B, with only five previous pivoted thruster flights, had to think about what control inputs to make, but nevertheless, had the vehicle under control from takeoff to landing. The vehicle initially drifted to the rear and to the left, however the pilot put in the proper corrective control. With longer flight time, the pilot could have translated to any desired point to land.

2. Effect of Underarm Supports

Initial flights were made with underarm supports for the pilot because previous flight experience with a smaller vehicle indicated that the pilot required a positive indication of lateral trim position. In addition, the stabilizing of the upper torso allowed the pilot to put in small and precisely controlled lateral inputs by motion of the lower torso only. In addition, the underarm supports provided the pilot with a feeling of security and of being part of the vehicle. However, the initial flights at 23.5 slug-ft^2 pitch inertia indicated that insufficient lateral control power was available, so the underarm bars were removed to allow greater lateral freedom of pilot motion. Forearm rests were provided to give the pilot a better sense of feel of his neutral trim position.

3. Pilot Platform

The first 16 kinesthetic flights were made with the footpans, that the pilot stands on, at a separation distance of 8.5 inches, center to center. The remaining kinesthetic flights were made with a wider platform allowing up to 19 inches center to center foot spacing to provide the pilot with more lateral stability. The wider stance improved the ability of the pilot to control the vehicle lateral motion.

4. Ground Effect

The rocket exhaust, deflecting from the floor and striking the vehicle, produced a destabilizing effect when the vehicle was within about three feet of the floor. This was quite noticeable to the pilots and added to the difficulty of taking off and landing with kinesthetic control. Later flights were started from a tethered position in the air which eliminated the ground effect and generally resulted in smoother starts. The ground effect could be easily overcome with pivoted thruster flights. These all took off from the floor. The control inputs could be applied more quickly and greater control power was available.

5. Trim Balance

At initial lift-off, if the vehicle and pilot combined center of gravity is not balanced on the thrust vector, the vehicle will rotate immediately and will start to translate. The pilot corrects for it by applying control in the opposite direction. This is done more quickly with pivoted thrusters where only the thrusters need move to cause vehicle horizontal motion. However, it is a significant problem with kinesthetic control since the entire vehicle must change angular attitude to make the correction. If the pilot happened to be in the proper trim position, the lift-offs were smooth. If not, the unbalance, coupled with the destabilizing ground effect, caused considerable angular and translation dispersions while taking off.

6. Tether Effect

The safety tether, described in Section II.B was attached to the vehicle at a point about 3.5 feet above the center of gravity. The small force required to overcome the friction of pulling the cable over the overhead pulley caused a disturbing pitch or roll moment to the vehicle which often resulted in the vehicle becoming uncontrollable. It was hoped that high enough flight proficiency would be reached to permit the vehicle to be flown without a safety tether. It became apparent that kinesthetic control was so marginal that it would be hazardous to fly without the safety tether. The program was shut down for a period and the safety tether system redesigned and modified. This resulted in a smaller disturbing moment on the vehicle as it pulled the tether cable over the overhead pulley. When the vehicle remained within a few feet of a line directly under the overhead rail on which the pulley traveled, the cable friction caused little or no disturbance to the vehicle. However, wide lateral excursions of the vehicle resulted in disturbing moments throughout the program.

7. Flight Time

The flight time of 20 seconds required a high level of concentration on the part of both pilots. Immediately after take-off they were required to concentrate on the landing maneuver, with little time to test and feel out the controls. Both pilots reported that with two to three minutes of flight time per flight, the learning would have been much easier and faster and would probably have resulted in improved Cooper ratings.

D. SIMULATED LUNAR GRAVITY FLIGHT RESULTS

These flights were flown with a gimbal mounted, tether supported vehicle shown in Figures 2 and 3 and the flight sequence tabulated in Table VII. One propellant load permitted 40 seconds of flight duration. The constant force tether which supported 5/6 of the vehicle weight provided absolutely safe flight. It prevented the vehicle from tipping over during landing and was provided with a safety snubber which could be actuated by the pilot at any time he desired. Thus the pilots were not hesitant to continue trying to control the vehicle in spite of unacceptably poor handling qualities. This resulted in flights of longer duration than the 1 g flights.

Vehicle response was considerably slower than on the 1 g flights. Even with maximum pilot control input, the vehicle, once started, could not be stopped within the length of the overhead rail.

The pilots often reported that control seemed reversed. When the pilot leaned forward, to start the vehicle moving forward, the vehicle would start moving backward. This was caused, in part, by an initial transient nose-up reaction of the vehicle to the pilot's nose down body rotation. This condition may have been further aggravated by a tendency on the part of the pilot to bend his body as he leaned forward. This would result in his center of gravity moving off the pilot suspension pivot axis. Depending on the direction of bending, this could add to or subtract from the control moment being imposed on the vehicle.

The last two kinesthetic flights were made with the pilot taped rigidly to rods to prevent bending of his body. The control response was correct although very slow. On the first flight the pilot controlled the vehicle from takeoff to landing although the pitch angles that developed were high because of lack of experience for this configuration. On the second flight, the pilot got too far behind in trying to keep up with and stop the vehicle motions and aborted. A second attempt resulted in a good flight.

Pilot A felt that he might learn to fly the vehicle with practice, but, as in earth gravity, felt that final translation corrections prior to landing would be very difficult and time consuming. Pilot A gave Cooper ratings for the final two flights:

Pitch	-	5
Roll	-	5
Yaw	-	7
Throttle	-	7 (Due to the low throttle ratio on the test vehicle.)

Two 1/6-g flights were made by Pilot A with pivoted thrusters and a vehicle pitch inertia of 157 slug-ft^2. Control was much more positive and rapid although the Cooper ratings were identical to those for kinesthetic control. The control sensitivity on this vehicle was considerably lower than this pilot had flown on other thrust vector controlled vehicles. Control sensitivity can be increased considerably and would be expected to result in better Cooper ratings. Pilot A reported that final translation corrections prior to landing were easier than with kinesthetic control, because vehicle translation occurred immediately with a control input. It was not necessary to wait for the vehicle to pitch, as with kinesthetic control.

1. Effects of Vehicle Inertia

The kinesthetically controlled series consisted of three flights with the vehicle pitch inertia at 50 slug-ft^2, four flights at 39 slug-ft^2 and six flights at 157 slug-ft^2.

As vehicle inertia increased, vehicle response was noticeably slowed. As in the 1 g flights, the slowness did not seem to impair the ability to hover, but did impair the ability to bring the vehicle to a stop at a predetermined spot, within the flight time permitted by the propellant supply. At no inertia tested would either pilot have considered the control power acceptable for flight without a safety tether.

2. Effect of Short Flight Time

The flight time of 40 seconds limited the evaluations to short, low speed flights. It slowed down the pilot learning and is reflected adversely in pilot ratings but to less an extent than the 1 g flights.

3. Effect of Flight Envelope Limits

The length of the overhead rail limited the flights to about 100 feet. Due to the constant tension tether, the vehicle was limited to very small lateral translations. The constant tension device also limited the altitude to 10 feet. Flying a straight line added to the pilot workload. The altitude limit was never approached and did not affect the evaluations.

4. Effect of Throttling Ratio

References 1 and 2 show that efficient lunar flight will require a throttling ratio of at least 7 to 1 and a maximum thrust to lunar weight of 2.0. The test vehicle had a throttling ratio of 4.3 and a maximum thrust to lunar weight of about 1.2. Although the test vehicle acceleration capability was much lower than for a lunar vehicle, the flight envelope and flight time limits would not have permitted the use of a higher thrust. The throttling ratio did not affect the evaluations.

5. Effect of Constant Tether Force

To faithfully simulate lunar gravity, the vehicle should always fly at 16.1 percent of earth gravity. This requires that the tether force should decrease as propellant is consumed. The constant tension device provides a constant tether force which has the effect of decreasing the simulated gravity as propellant is consumed. The result is to decrease the control sensitivities in all three axes as propellant is consumed.

The constant tension device also has a hysteresis force of about 40 pounds. This caused a stabilizing effect on flight altitude and required a large throttle reduction to descend, accompanied by a similar reduction in control power.

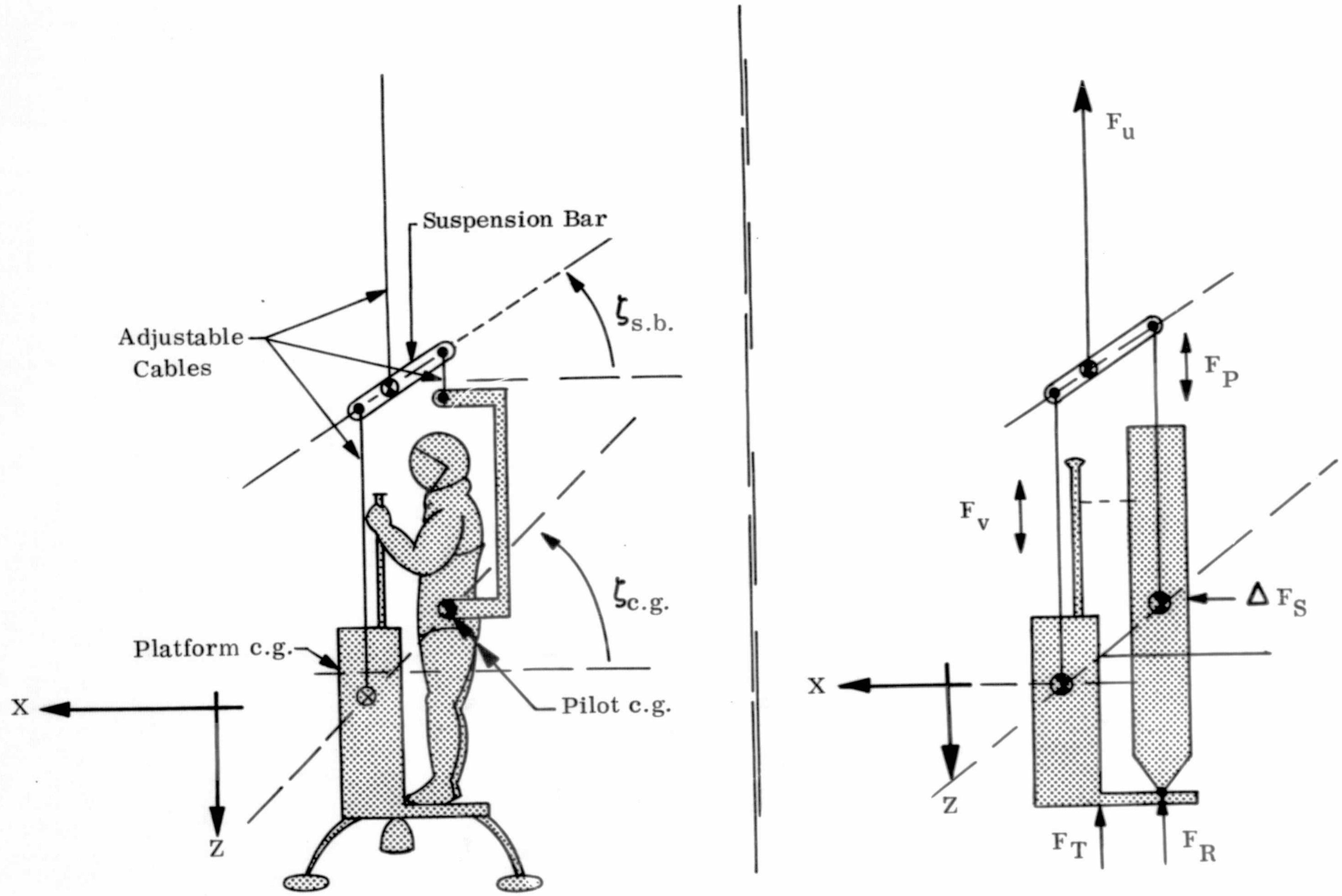
6. Effect of Body Bending

The lunar simulation with independent pilot suspension, relies on the pilot being suspending at his center of gravity. Any motion, such as bending the body at the hips, or movement of head and limbs, which moves the center of gravity away from the suspension gimbal axes, will produce a moment about the suspension point that is transferred to the vehicle. This moment is caused by the tether supported portion (or 5/6) of the pilot's earth weight, whereas the simulated kinesthetic control moments are generated by 1/6 of the pilot's earth weight. Therefore, the moments due to movement of the pilot's center of gravity from the suspension point can cause considerable error in the vehicle control moment and can easily overcome the desired control moment. This happened in the early flights and, for those flights, had an adverse effect on the evaluations.

7. Suspension System Geometry

The suspension system is shown schematically in Figure 9. The main support cable provides a constant upward force equal to 5/6 of the total system weight. The cable is attached to a pivoting bar, which supports the vehicle at one end and the pilot at the other. The ratio of the arm lengths is such that 5/6 of the vehicle weight balances 5/6 of the operator's weight. The vehicle is supported at its center of gravity by a two-axis gimbal. The operator suspension supports the operator at his center of gravity with a two-axis gimbal. The main support cable supports the entire system at the system center of gravity.

If the suspension bar and the line between the pilot and vehicle centers of gravity are not parallel, unwanted forces and moments are generated when the vehicle and pilot suspension cables are not parallel, as in the case when the pilot leans forward or backward for control. During the tests, the nominal suspension bar angle ($\zeta_{s.b.}$) was 45° and the nominal c.g. line angle ($\zeta_{s.g.}$) was 69°; the effect was to reduce the pilots' control moment by approximately 42%. The vehicle can be considered to have an "effective" inertial 72% higher than its actual value.



(Not to Scale)

Figure 9. 1/6 g Flight Simulation System

V. CONCLUSIONS

Conclusions reached are as follows:

a) In earth gravity, the flyability with kinesthetic control was very poor over a vehicle inertia range from 23.6 to 130.1 slug-ft^2. The ability to stabilize the vehicle flight in hover improved with increasing inertia. Final translation corrections prior to landing were difficult. With sufficient inertia for the vehicle to be flyable, further increases did not improve the ability of the pilot to control the vehicle to a precise landing spot.

b) Thrust vector control at a vehicle inertia of 130.1 slug-ft^2 resulted in much better characteristics than kinesthetic control. Final translation corrections prior to landing could be made more rapidly with thrust vector control than with kinesthetic control.

c) In simulated lunar gravity with an effective moment of inertia range of 55 to 265 slug-ft^2, vehicles can be flown kinesthetically but vehicle response is very slow and final translation corrections prior to landing are very difficult and time consuming.

d) In simulated lunar gravity pivoted thrusters provided better controllability than kinesthetic control, at a vehicle pitch inertia of 157 slug-ft^2.

e) The ability to stabilize vehicle flight in hover was better in simulated lunar gravity than in earth gravity, for a given vehicle inertia. However, the slower response in lunar gravity made precise landing more time consuming and required greater pilot anticipation of commands. It was not possible to develop a ratio of lunar vehicle inertia to earth vehicle inertia for equivalent handling qualities.

VI. REFERENCES

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APPENDIX A

SUMMARY OF TEST FLIGHTS

The test flights conducted under NASA Contract NAS 9-8777, are summarized in Tables A-I for earth gravity and A-II for simulated lunar gravity. The tables indicate the vehicle configuration, pilot identification, vehicle inertia about the vehicle center of gravity, and general comments. All flights were with kinesthetic control except where noted that pivoting thrusters were used. Underarm supports were used on 1-g flights where indicated. No underarm supports were used in the 1/6-g flights. The 1-g flights had a maximum flight time of 20 seconds and the 1/6-g flights had a maximum flight time of about 40 seconds.

TABLE A-I

SUMMARY OF FLIGHTS IN EARTH GRAVITY

Flight No.	Configuration	Pilot	Vehicle Pitch Inertia	Results and Pilot Comments
T-1 10/3/68	Ballast frame on, ballast inboard, underarm supports	A	47.3 (85.3 with pilot)	Hover flight to feel out controls. Lateral inputs from ground effect and the tether. Throttle and yaw controls stiff. Vehicle slightly nose heavy. Very difficult to control.
T-2 10/3/68	No change	A	47.3 (85.3 with pilot)	Rebalanced to eliminate nose heaviness. Flew with tether tight to feel out yaw for control cross coupling. When yaw control was applied, vehicle appeared to pitch nose down and roll in the direction of yaw. May be due to jet impingement on frame.
T-3 10/4/68	Ballast frame off, ballast inboard, underarm supports	A	23.6 (61.6 with pilot)	Nose heavy on first try. Rebalanced. Lifted off on second and third tries but pilot could not control the vehicle.
T-4 10/4/68	No change	B	23.6 (61.6 with pilot)	On two tries the vehicle rolled to the right at lift off and was snubbed. On another try - good liftoff. During translation, tether trolley lagged causing vehicle to pitch up and abort. Pilot feels it can be flown.
T-5 10/7/68	No change	B	23.6 (61.6 with pilot)	First try - aborted. Second try - good take off. Hovered then started to translate. Tether lagged and pitched the vehicle back but a landing was made. Third hop - good takeoff. Appeared to get nose down pitch with yaw control input. Pilot landed successfully.
T-6 10/7/68	No change	B	23.6 (61.6 with pilot)	First try - aborted. Second try - good takeoff. Oscillated in pitch and roll during translation but was stopped by pilot and a landing was made. Third try - good takeoff, rose to two feet and landed. Pilot feels he is learning to fly the vehicle.
T-7 10/8/68	No change	A	23.6 (61.6 with pilot)	First takeoff good. Lost control in translation and aborted. Second takeoff good, translated with pitch and roll oscillations and landed. Third takeoff good, rose one foot and landed.
T-8 10/16/68	No change	A	23.6 (61.6 with pilot)	First flight started suspended on tether 1-1/2 feet above floor. Good start, fair flight and fair landing. Operator reports vehicle "barely controllable."
T-9 10/17/68	No change	B	23.6 (61.6 with pilot)	First flight started suspended on tether. Fair flight and landing. Second flight from ground - poor.
T-10 10/17/68	No change	B	23.6 (61.6 with pilot)	Same as T-9. Pilot feels complete lack of control.
T-11 10/25/68	No change	A	23.6 (61.6 with pilot)	First flight started tethered, Second from ground. Both good flights with landings.
T-12 No flight	No flight			
T-13 No flight	No flight			
T-14 2/12/69	Ballast frame off, ballast inboard, no underarm supports	A	23.6 (61.6 with pilot)	Several unsuccessful attempts to takeoff. Pilot feels too loose relative to vehicle and cannot control it.
T-15 2/17/69	Same as T-14 except forearm supports added.	A	23.6 (61.6 with pilot)	Two tries suspended on tether - Difficulty getting stabilized and aborted first one. Second flight much improved but did not land. Third try from the ground - Oscillated taking off then smoothed out. Aborted at burnout.
T-16 2/17/69	No change	A	23.6 (61.6 with pilot)	Two tries from the air, one from the ground. Poor control and aborted all three. Pilot feels underarm supports are necessary.
T-17 2/19/69	Same as T-16 except wider-foot pads for better pilot lateral stability	A	23.6 (61.6 with pilot)	Pilot feels he has better control with wider stance. Had control initially but gradually lost it.
T-18 2/19/69	No change	B	23.6 (61.6 with pilot)	First try from the air, second from the ground. Was snubbed right at landing on first hop and landed on second. Feels ground effect up to about three feet. Feels it affects translation more than rotation. Pilot A commented that it looked better than any of his flights felt. Pilot B commented that it felt better than any of Pilot A's flights looked.
T-19 2/19/69	No change	B	23.6 (61.6 with pilot)	Control not as good as previous flight. Pilot feels he will never be able to make a good controlled flight from takeoff to landing.

TABLE A-I (CONT)

Flight No.	Configuration	Pilot	Vehicle Pitch Inertia	Results and Pilot Comments
T-20 2/20/69	Outboard frame added with ballast inboard	A	47.3 (85.3 with pilot)	Vehicle feels better than at the lowest inertia because angles develop slower and translations start slower. At the start of flight, pilot feels he has control but as the attitude angles increase, he loses it.
T-21 2/20/69	No change	A	47.3 (85.3 with pilot)	One long flight from the air with a landing, one short one from ground. Pilot inputs very similar to those with underarm supports i.e., by moving his hips. Although he flew the vehicle to a landing pilot does not feel that it was too well under control. Yaw control appeared to be adequate.
T-22 2/20/69	Ballast moved outboard	A	130.1 (168.1 with pilot)	Best flight to date on this vehicle. Two hops, both from the air, both snubbed without landing. Pilot feels he had better control than on any other flight.
T-23 2/21/69	Outboard frame, outboard ballast	B	130.1 (168.1 with pilot)	Two flights from the air. On first, climbed to a hover, started to descend and tether tightened causing diverging motion, was snubbed. Second started good, gradually lost control. Time constant has changed from low inertia but still difficult to fly. Pilot thinks that with 2-3 minute flights, he could learn to fly it. Pitch much easier to control than roll.
T-24 2/21/69	No change	A	130.1 (168.1 with pilot)	Three attempts. Started good but gradually lost control. Pitch better than roll, yaw power too low. Pilot feels it can be mastered easier than this vehicle at lower inertias but more difficult than a previous vehicle at 6 - 7 slug-ft^2 inertia. Cooper ratings: Pitch -5, roll -7, yaw 8.
T-25 2/26/69	Same but with pivoted thrusters	A	130.1 (168.1 with pilot)	Two hops. Good takeoffs. Controls too stiff, yaw no problem. Much better feeling to the pilot than kinesthetic. Nose down trim attitude.
T-26 2/26/69	No change	A	130.1 (168.1 with pilot)	Two hops. Roll control interference from honeycomb shock absorber.
T-27 2/28/69	No change	A	130.1 (168.1 with pilot)	Corrected roll interference from honeycomb. Very good flight. Pilot feels he could fly free in 10 flights. Cooper ratings: Roll -3-1/2, pitch -4, yaw -3, overall vehicle - 4.
T-28 2/28/69	No change	B	130.1 (168.1 with pilot)	Two hops. Vehicle felt much better than kinesthetic. Pilot had to think what to do to control vehicle. This would diminish with practice. Not conscious of any yaw inputs. Short flight time of great concern during entire flight. Pilot felt he had some degree of control for entire flight. Cannot give Cooper ratings without further flights.

TABLE A-II

SUMMARY OF FLIGHTS IN SIMULATED LUNAR GRAVITY

Flight No.	Configuration	Pilot	Vehicle Pitch Inertia	Results and Pilot Comments
T-1 1/21/69	Ballast on upper arms and lower front	A	50 (68 with pilot)	Two hops - both aborted at the end. Yaw control very low. Wallowing motions with very poor control.
T-2 1/23/69	No change	A	50 (68 with pilot)	First takeoff good. Started translating and could not stop. Second flight similar. Upper ballast weights restrict lateral control.
T-3 1/23/69	No change	A	50 (68 with pilot)	Rebalanced to reduce nose down tendency. Appeared tail heavy. Could not translate and landed with difficulty. No movie coverage.
T-4 1/24/69	Rearranged ballast for better pilot freedom	A	39 (57 with pilot)	First hop - pitched down, pilot could not stop translation. Second hop - similar, pilot could not get vehicle to pitch up by leaning back so pulled vehicle to him abruptly. Aborted.
T-5 1/27/69	No change	A	39 (57 with pilot)	First hop uncontrollable, second hop - hovered.
T-6 1/27/69	No change	B	39 (57 with pilot)	First hop - good takeoff, translated forward - could not stop. Second hop - same.
T-7 1/27/69	No change	B	39 (57 with pilot)	Tried to translate rearward but went forward on first hop. Second hop - started backward, tried normal control to go forward then jerked vehicle to him. Landed.
T-8 1/28/69	Ballast moved to longitudinal extension bars	A	157 (175 with pilot)	Good flight except translation could not be stopped. Second hop - could not start translating, pushed vehicle away from him and did start translating,then pulled it to him to stop. Control appears to be reversed.
T-9 1/28/69	No change	A	157 (175 with pilot)	Pilot feels that controls are reversed although it appeared to observers that the control inputs and response was correct.
T-10 1/28/69	No change	B	157 (175 with pilot)	Very good takeoff, From a steady hover, pilot leaned way back and remained steady. The vehicle gradually rotated forward. Photographs indicate that the pilots are bending their bodies sufficient to invalidate the simulation.
T-11 1/28/69	No change	B	157 (175 with pilot)	Substantiation of reversed control.
T-12 1/28/69	Pivoted thrusters	A	157 (175 with pilot)	Pitch and roll control very stiff. Some oscillation but fairly good flights. Good landing on first flight.
T-13 2/10/69	No change	A	157 (175 with pilot)	Yaw control low, pitch and roll response fairly good. Burned out without landing. Cooper ratings: pitch control -5, roll control -5, throttle -7, yaw control -7. Note: pivots are in a low control power position.
T-14 2/10/69	Kinesthetic with pilot tied to rigid poles to eliminate body bending	A	157 (175 with pilot)	Two hops with a landing on second. Control is in the proper direction but vehicle response is very low. Pitched up too far to stop at landing and started backwards. Cooper ratings same as T-13.
T-15 2/10/69	No change	A	157 (175 with pilot)	Two hops. On first - pilot got too far behind in trying to stop vehicle motions and aborted. Second flight good. Pilot feels that small translation corrections prior to landing will be very difficult.

APPENDIX B

1/6-g FLIGHT TEST DATA RECORDS

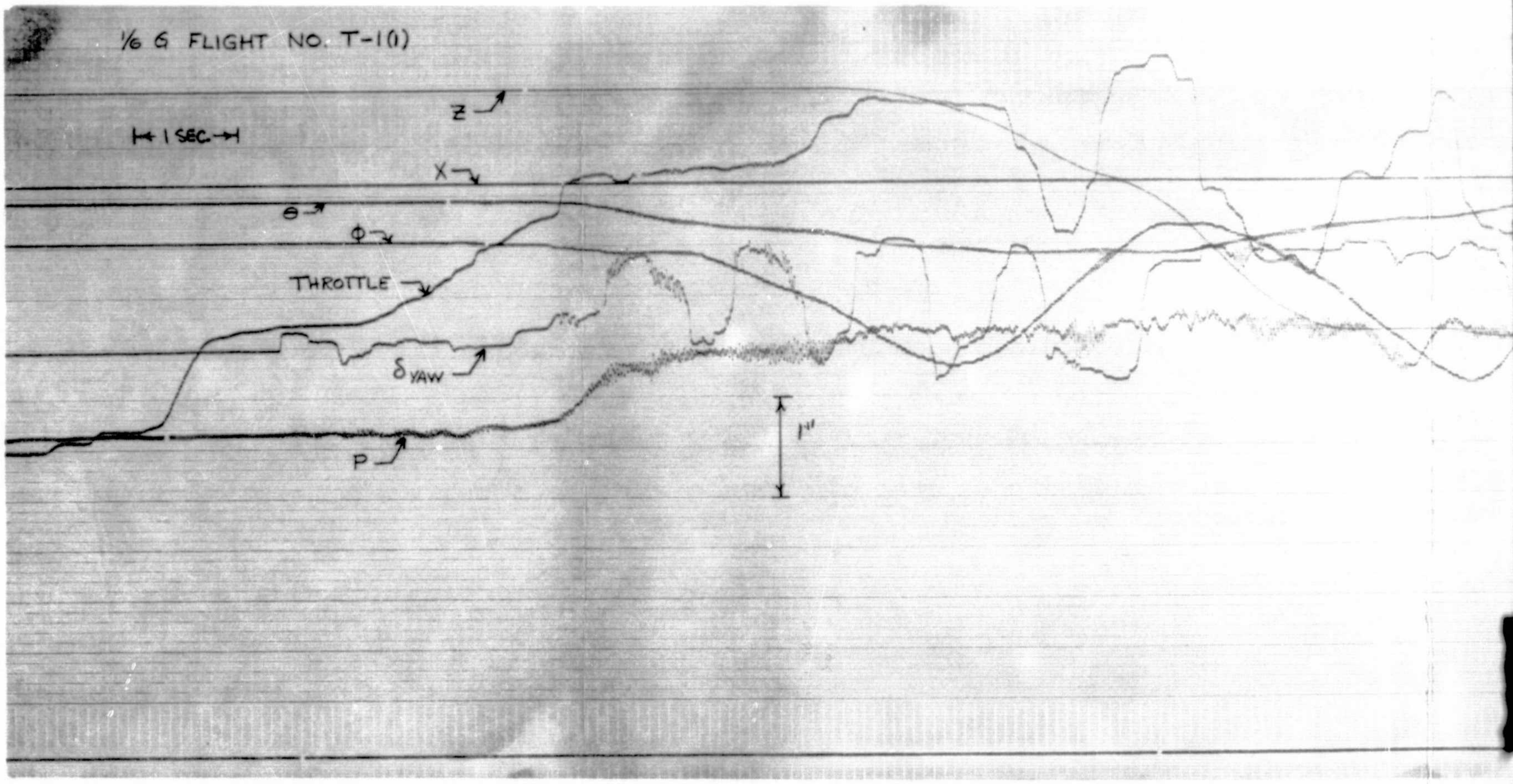
For all flights made in simulated lunar gravity, instrumentation was provided to give time histories of vehicle downrange, altitude, pitch attitude, roll attitude, throttle position, yaw control position and suspension cable tension. The records for each flight are presented in the following pages. The flight numbers correspond to those listed in the Flight Plan and Results Section for 1/6-g flights.

The oscillograph channels and vertical scales are identified as follows:

Osc. Channel	Symbol	Function	Vertical Scale
1	θ	Vehicle Pitch Attitude	16.10 deg/in.
3	ψ	Vehicle Roll Attitude	7.85 deg/in.
5	z	Vehicle Altitude	2.53 ft/in.
7	x	Downrange	25.50 ft/in.
9	ζ_{Yaw}	Yaw Controller Position	14.50 deg/in.
11	-	Throttle Controller Position	16.40 deg/in.
17	p	Suspension Cable Force	48.00 lb/in.

The suspension hysteresis was checked periodically by raising and lowering the vehicle prior to flight. These records are not shown but the hysteresis, which is due to the pliable bag in the suspension system and the safety snubbing mechanism, varied between 45 and 50 pounds.

The cable tension at the beginning of many flights has no significance prior to lift-off because the snubbing mechanism was in the snubbed position until lift-off. The abort of a flight is indicated by a very large oscillation in cable tension. The time scale is shown on each figure.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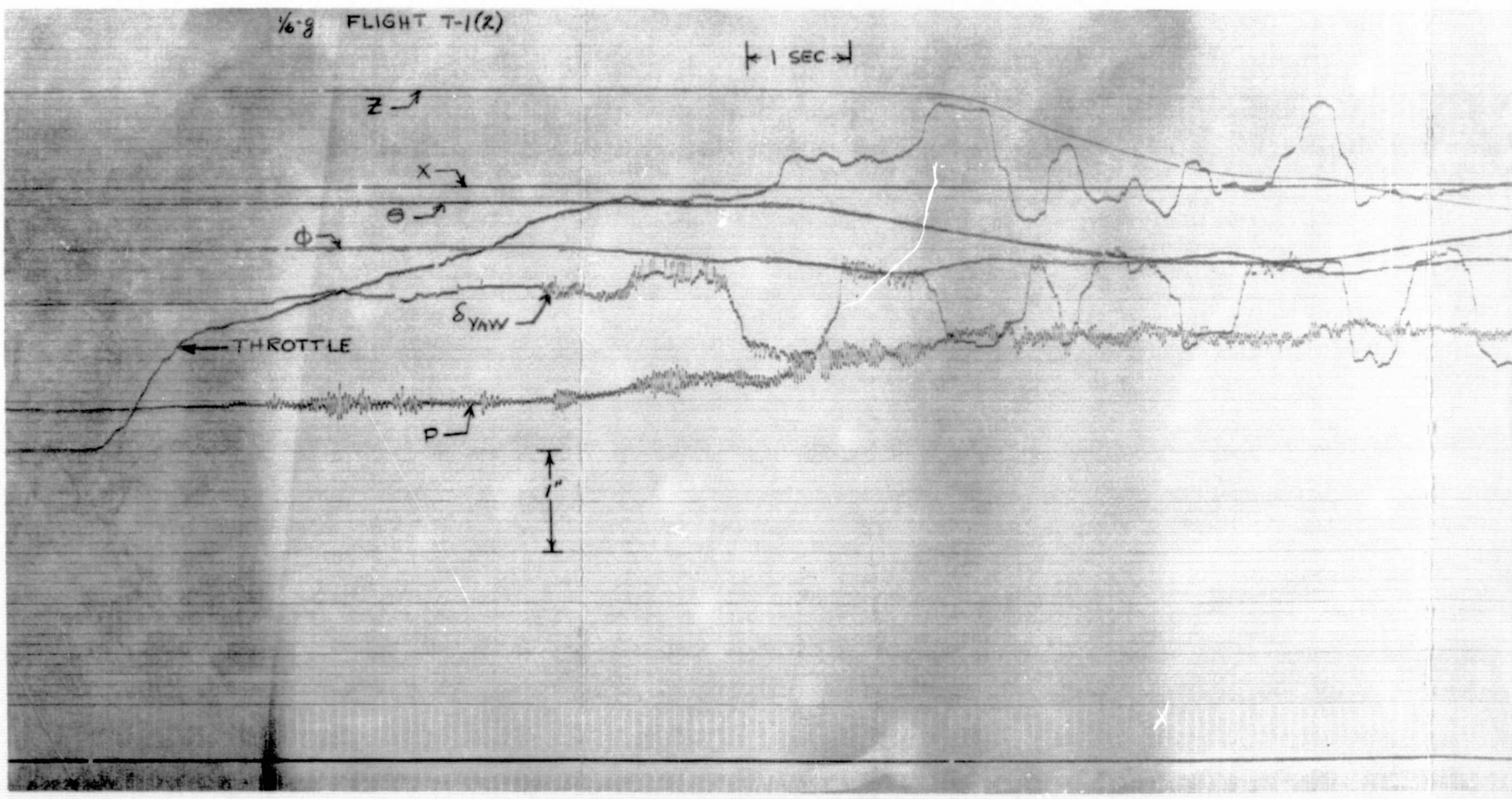
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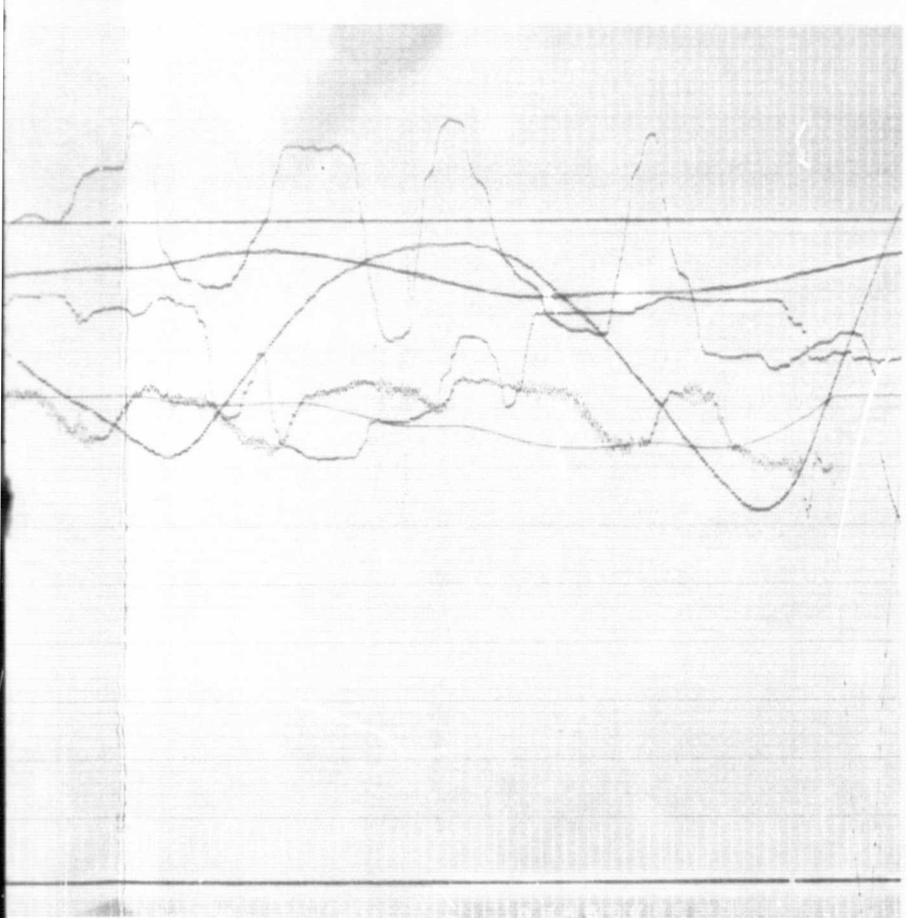

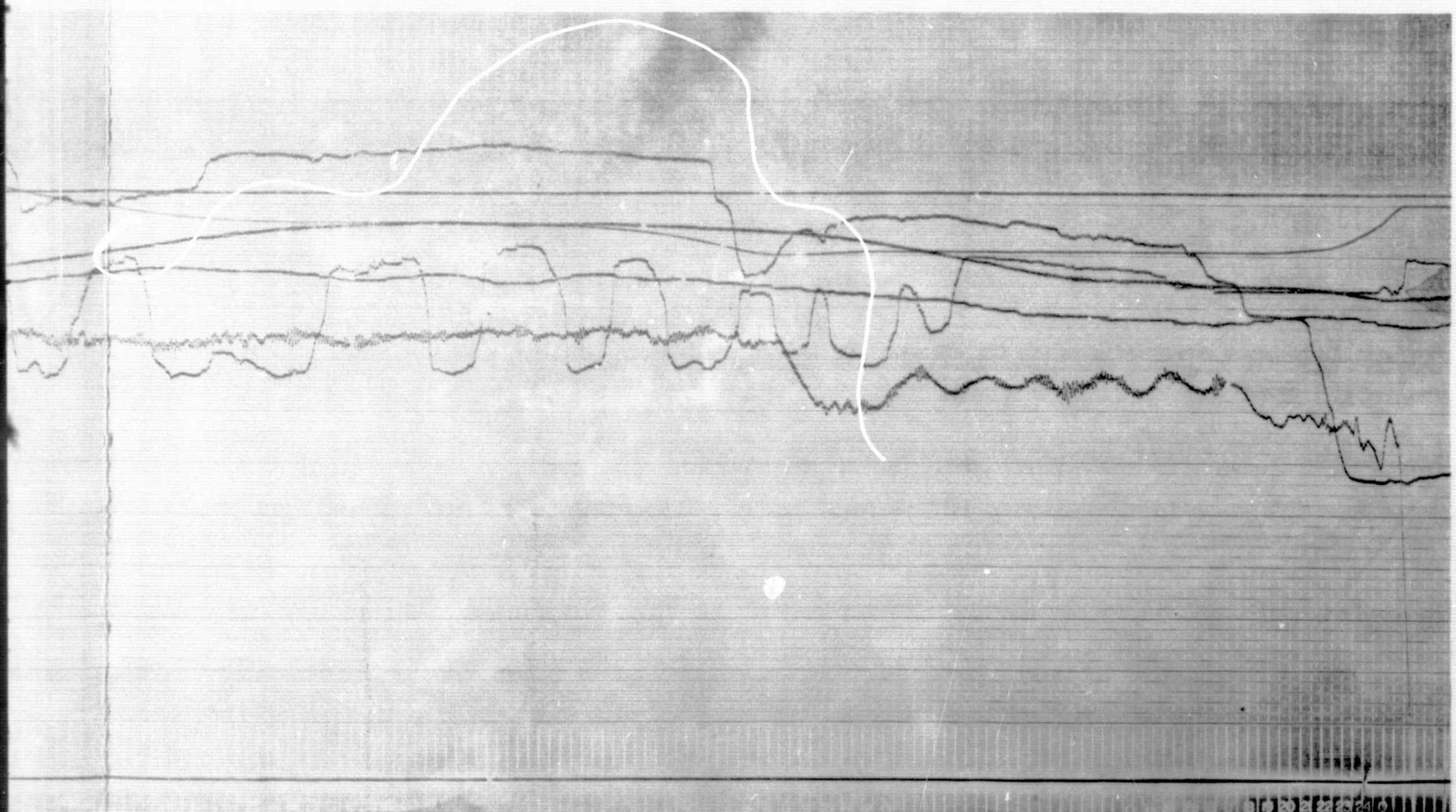

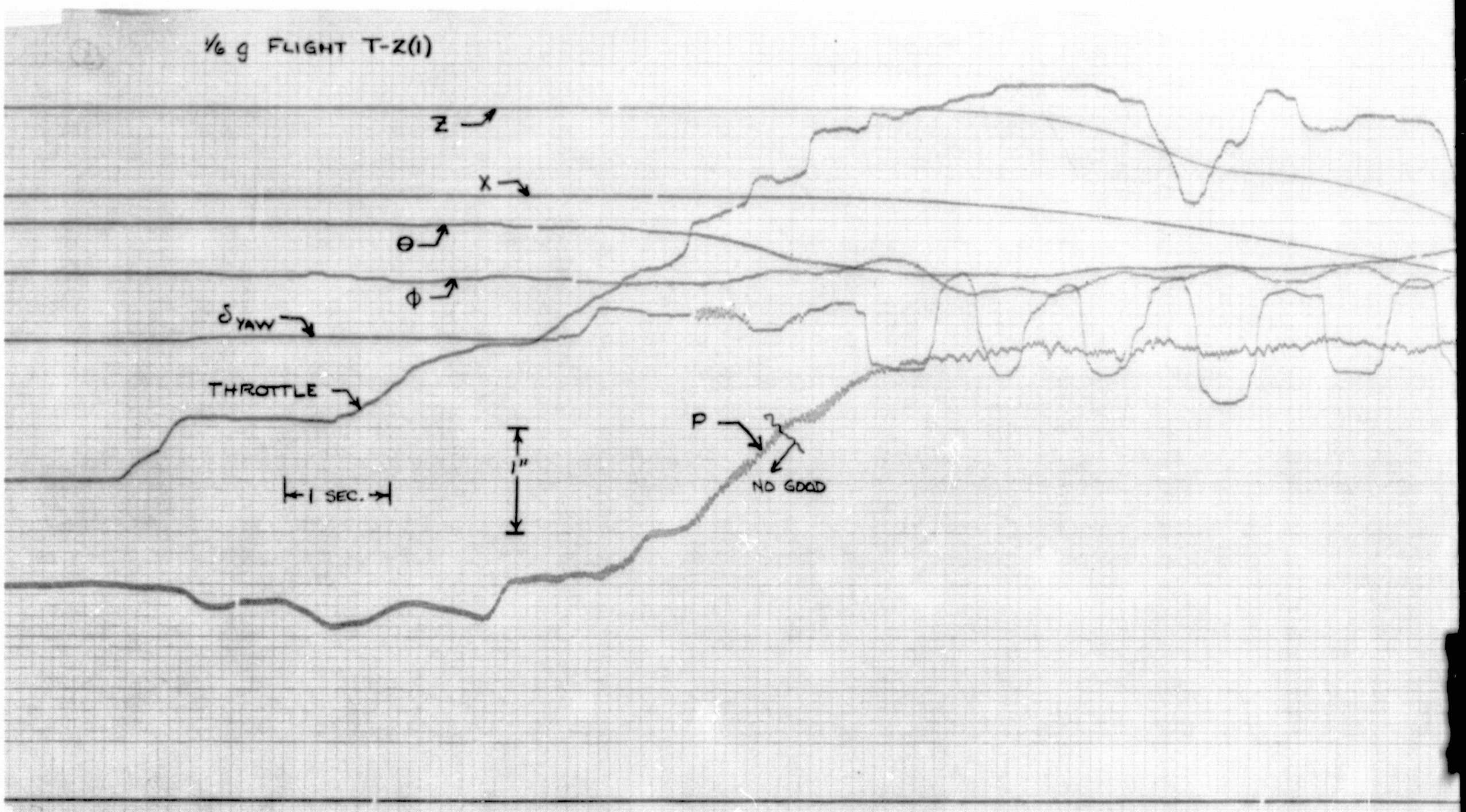
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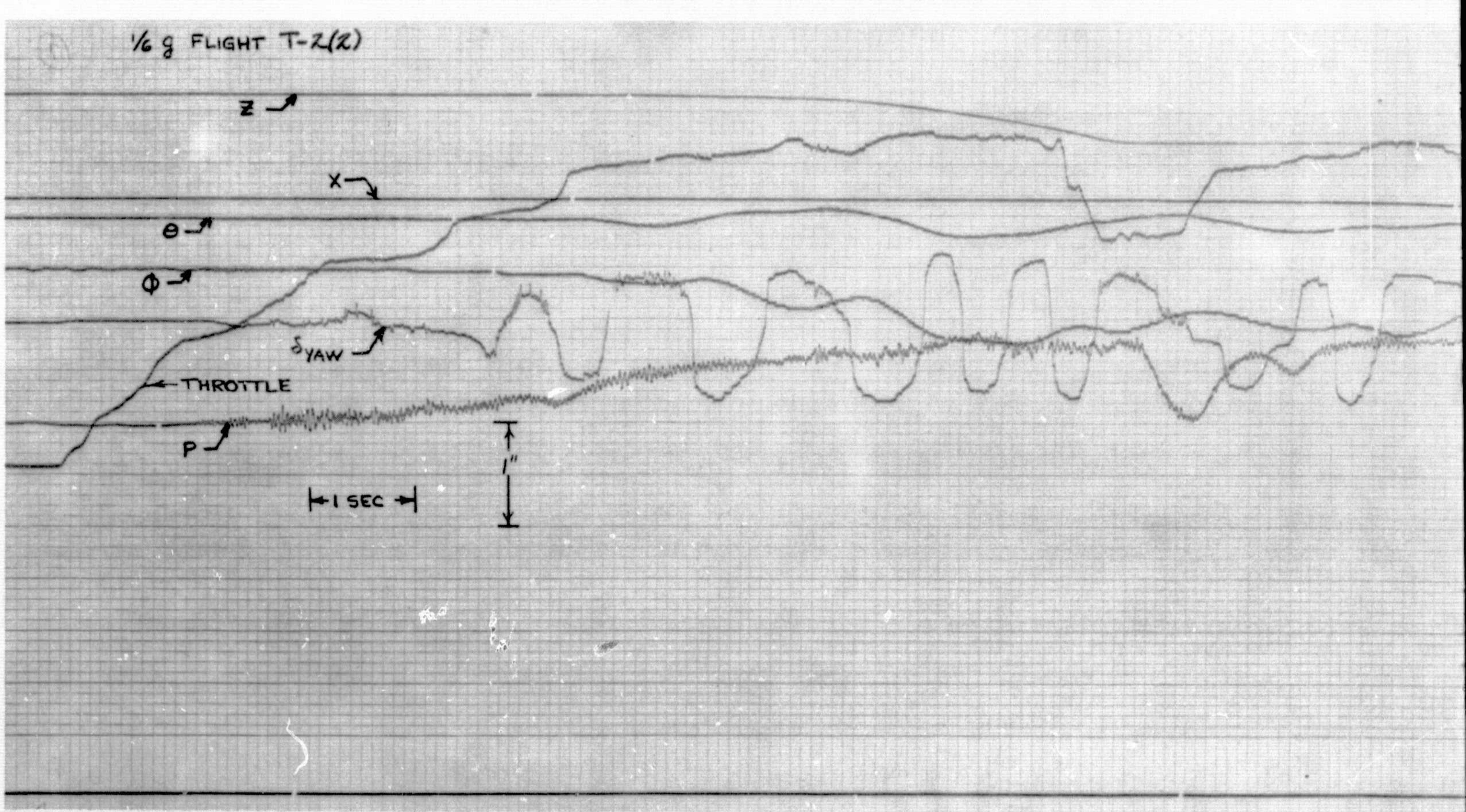
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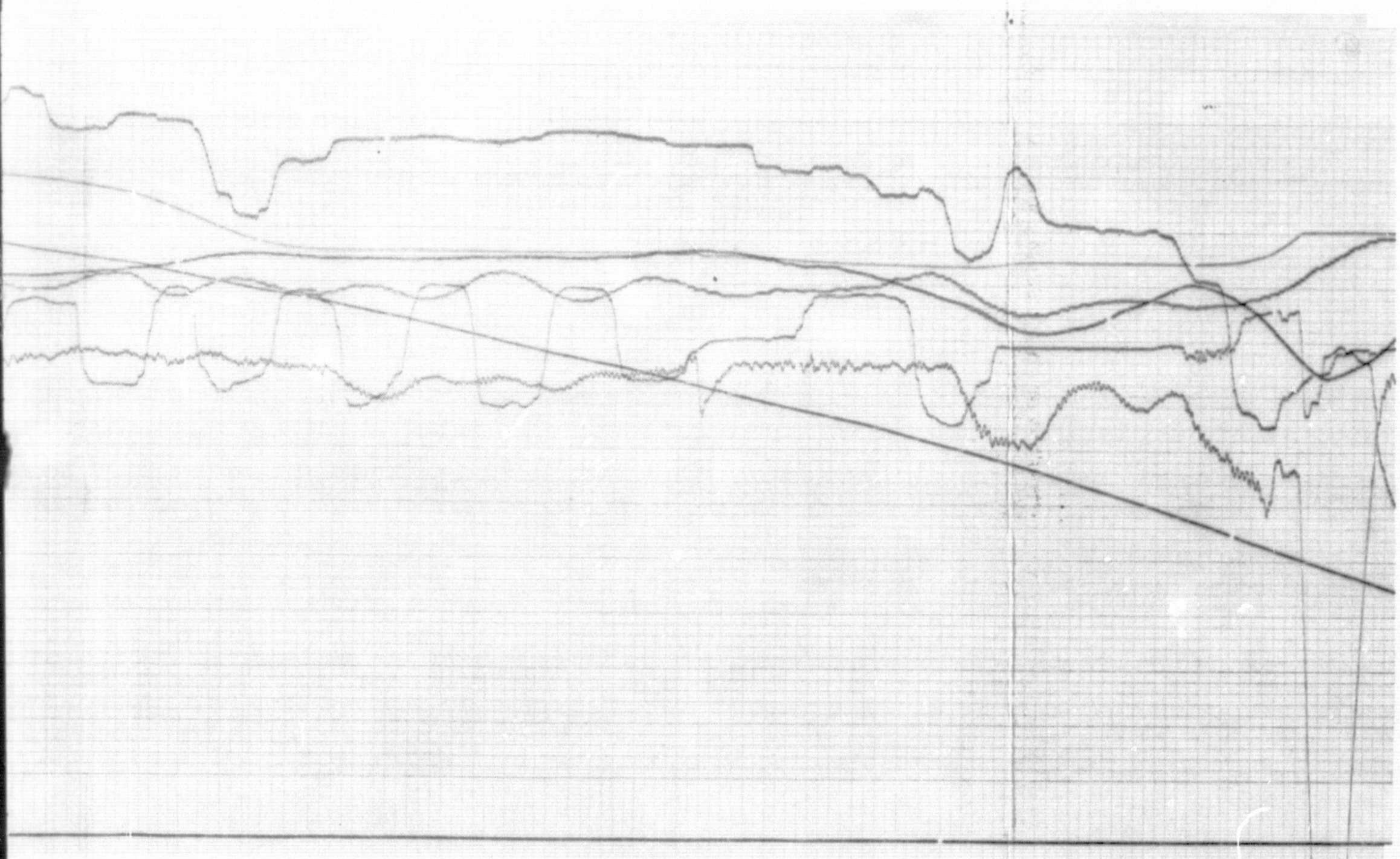

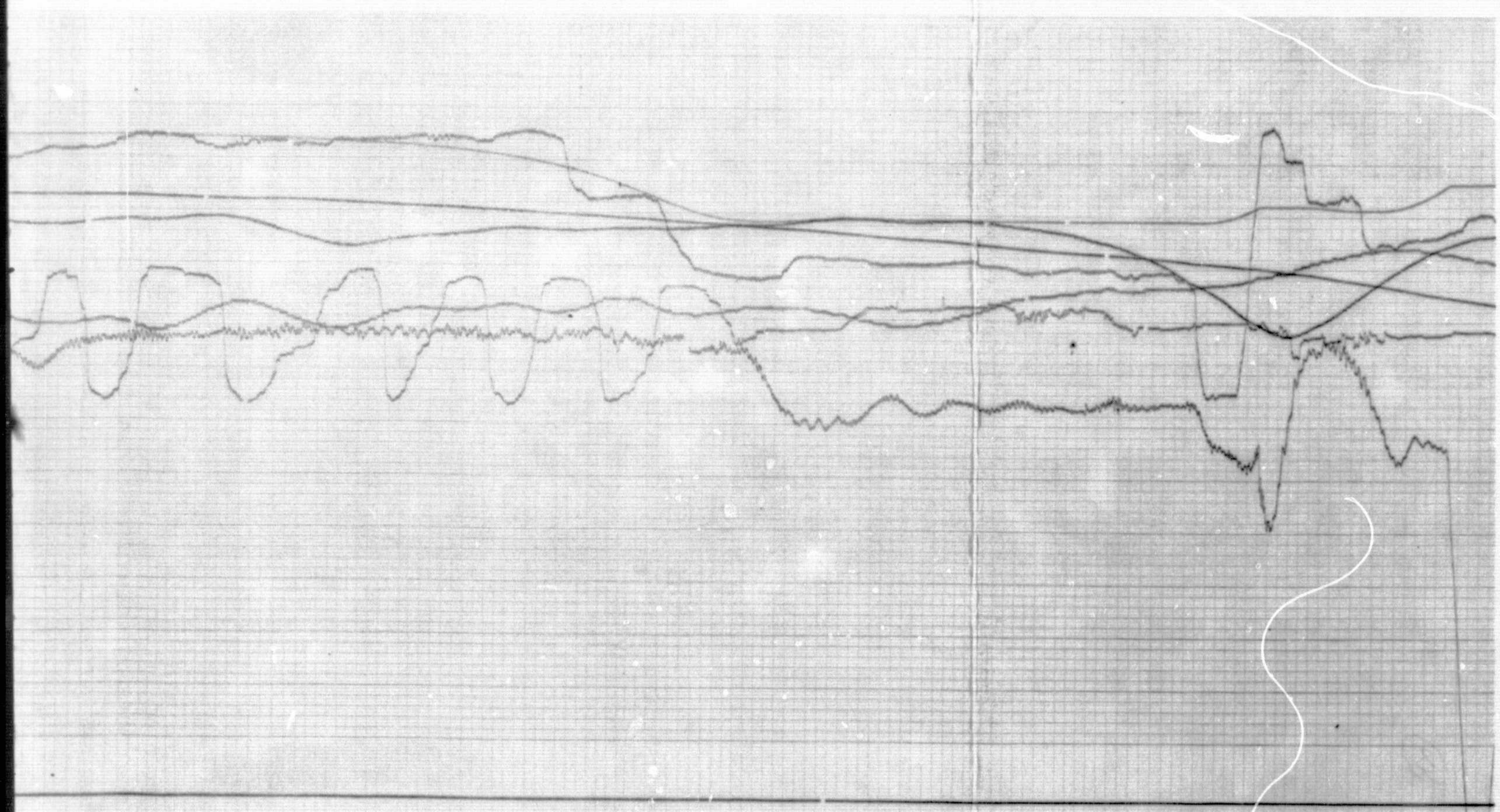

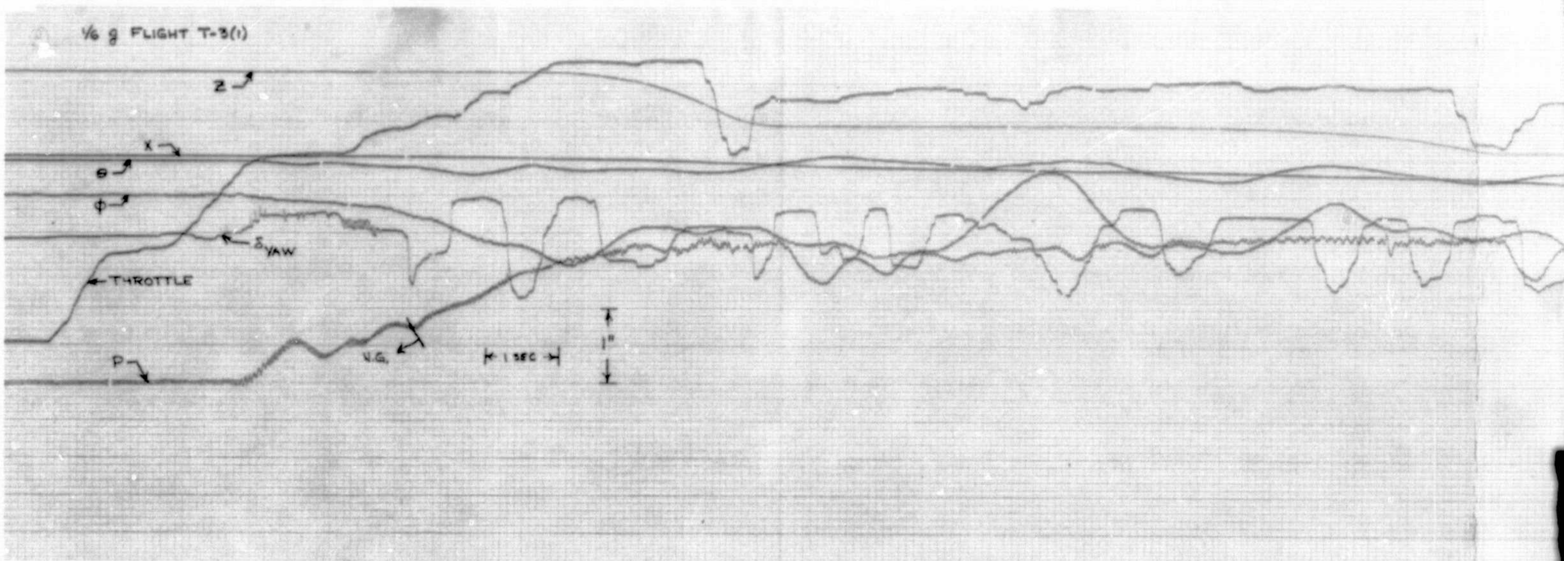

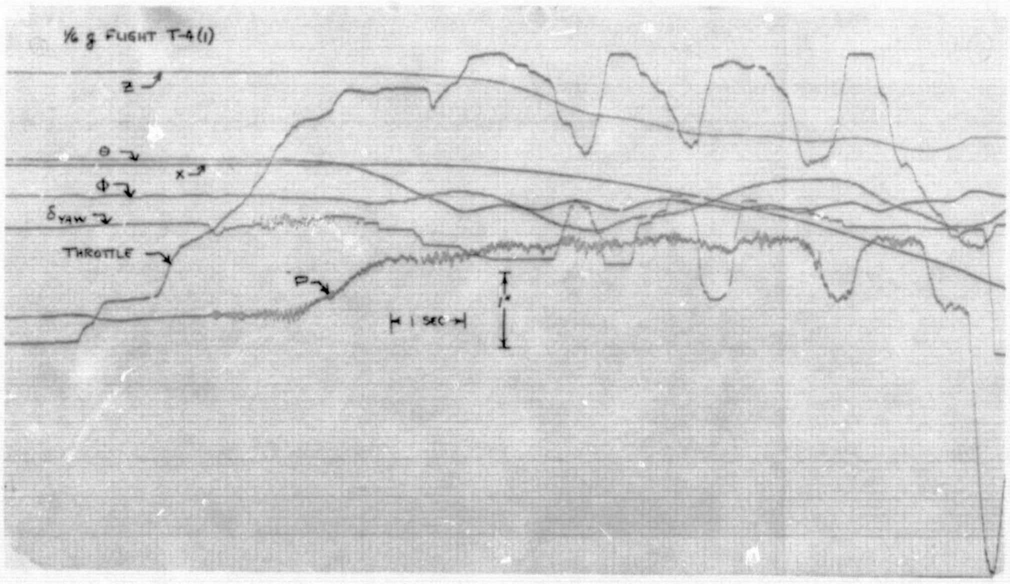

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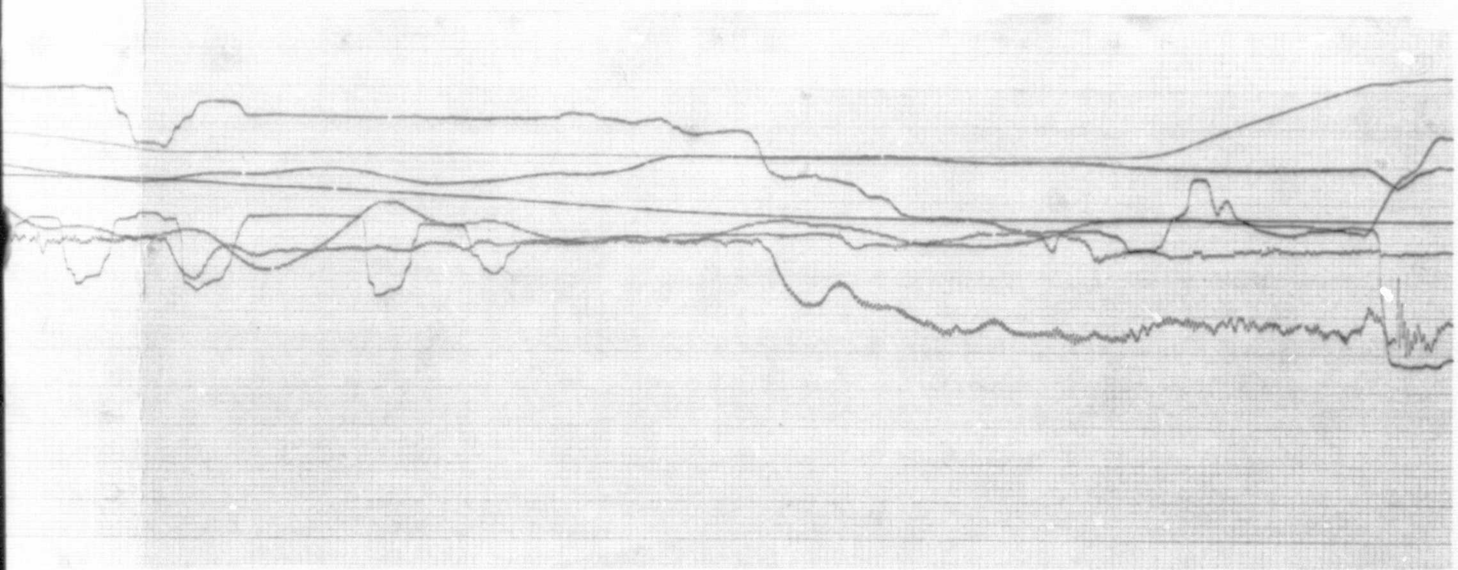

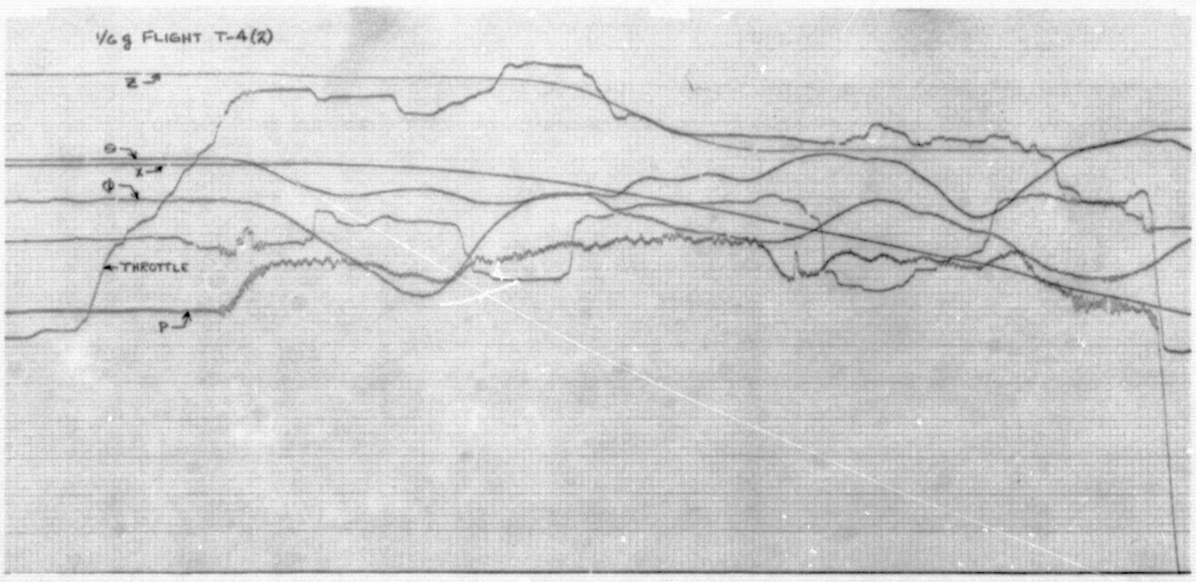

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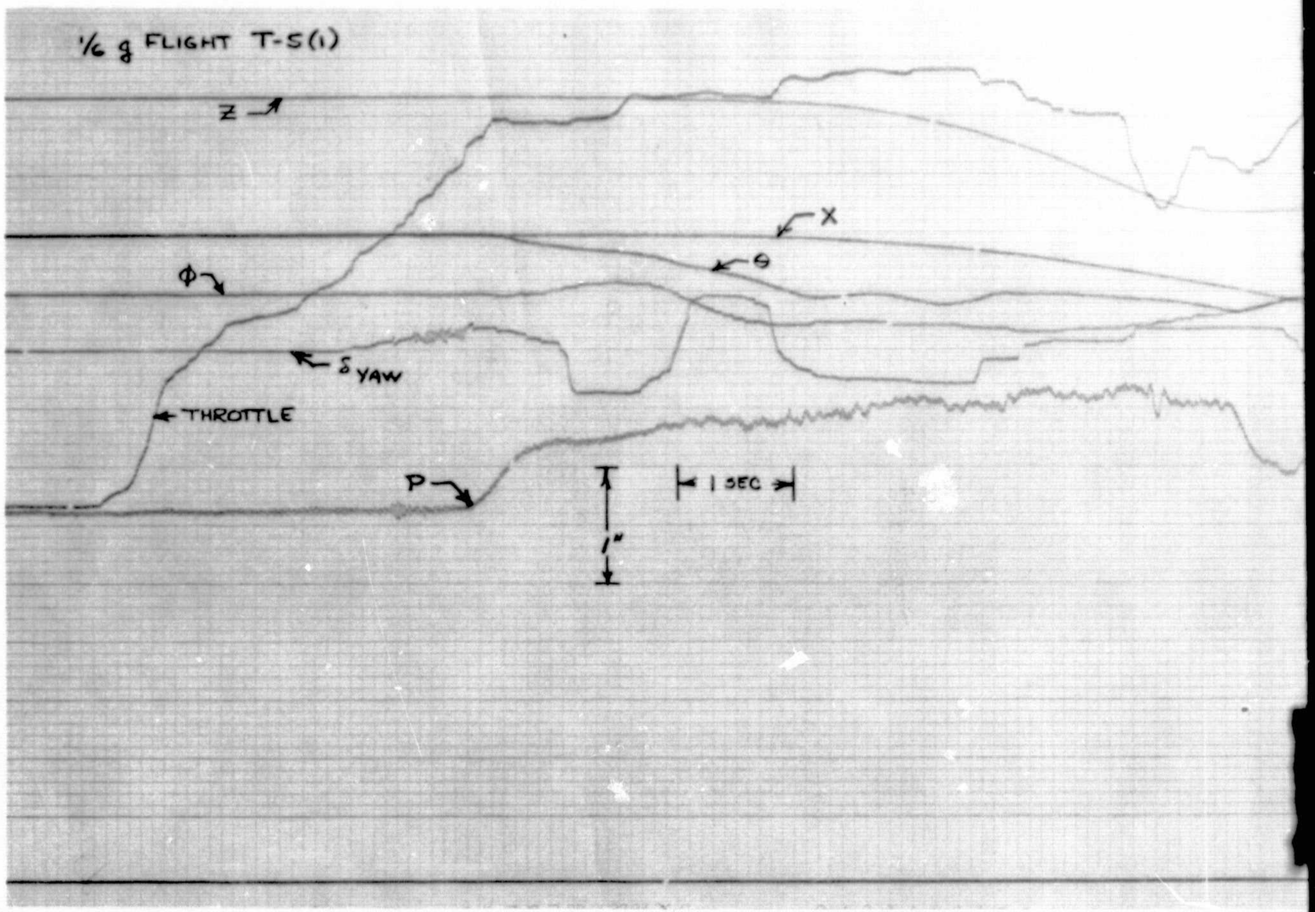

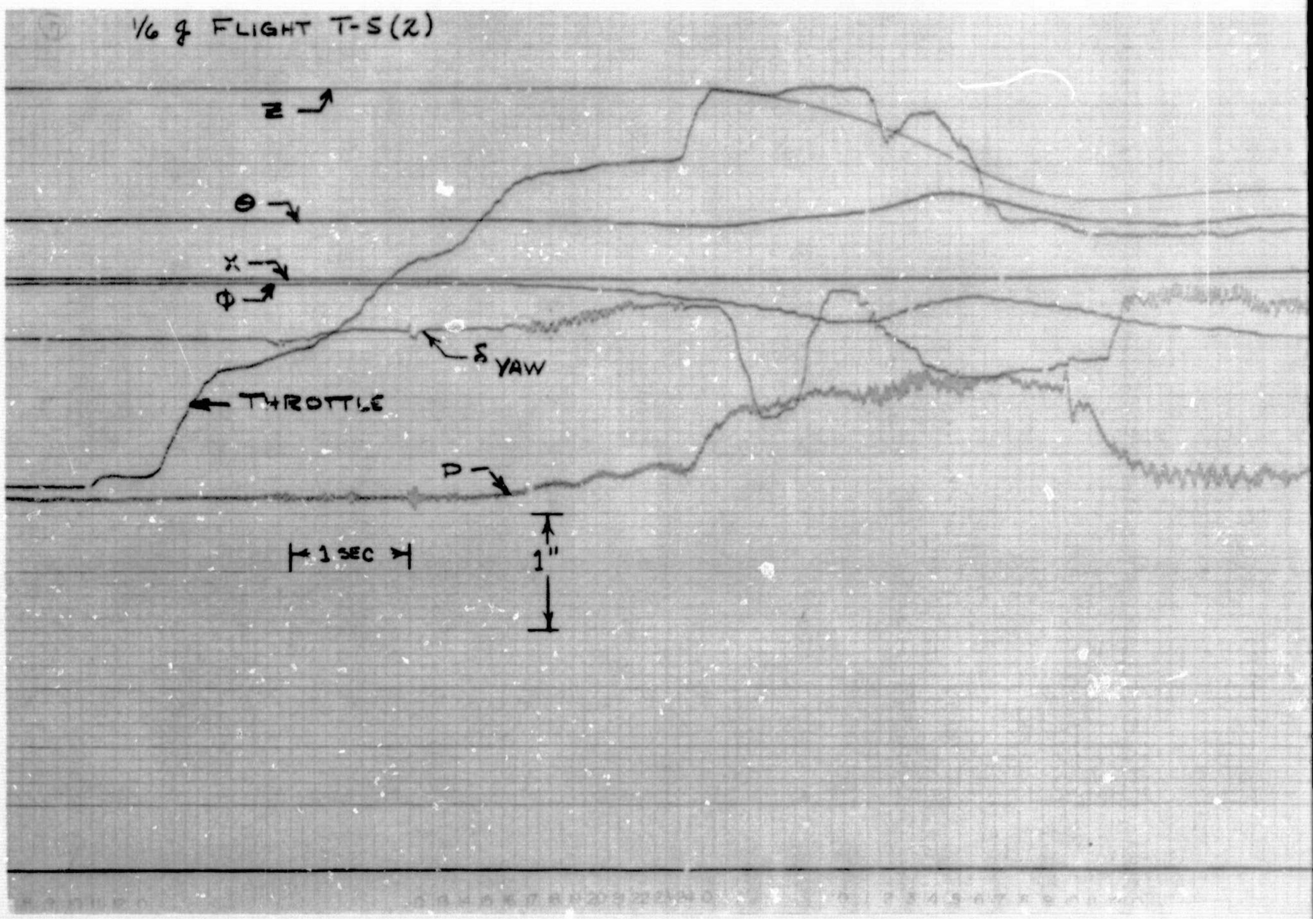

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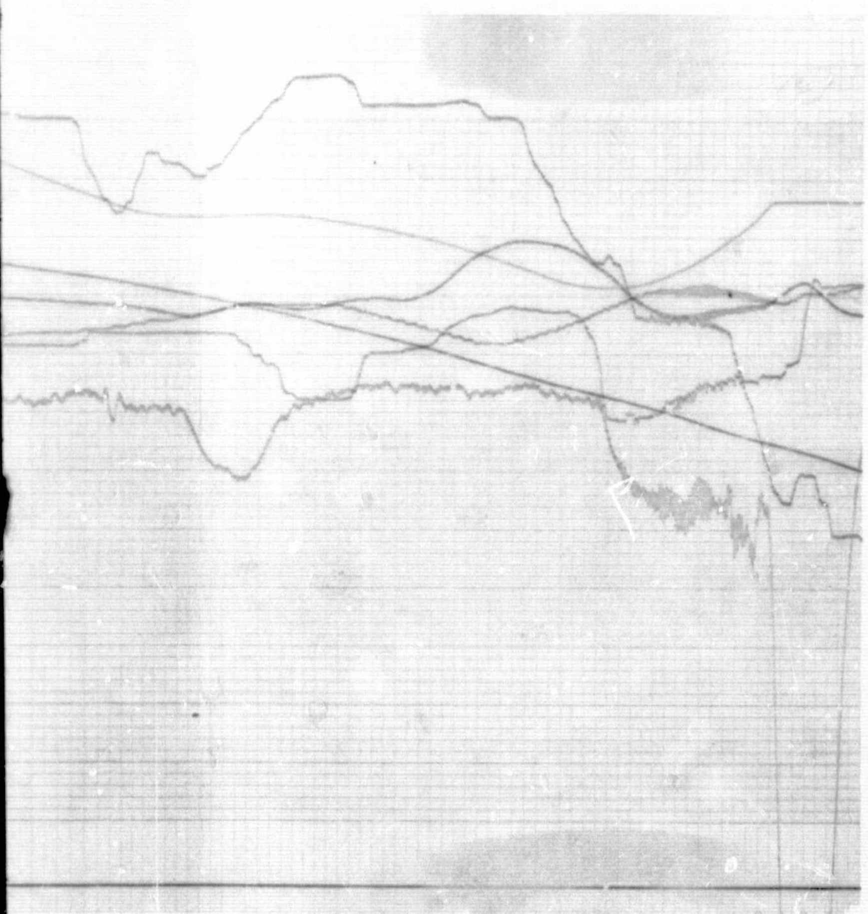

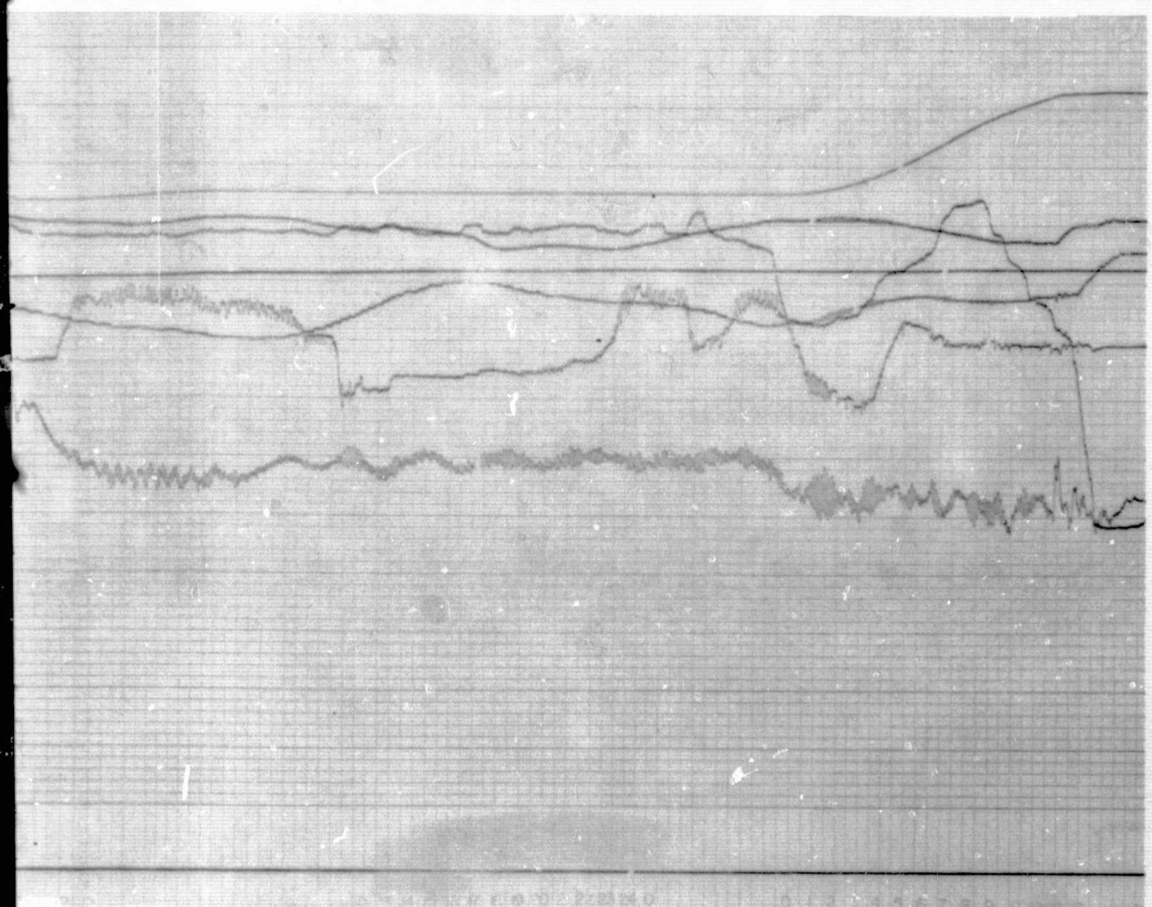

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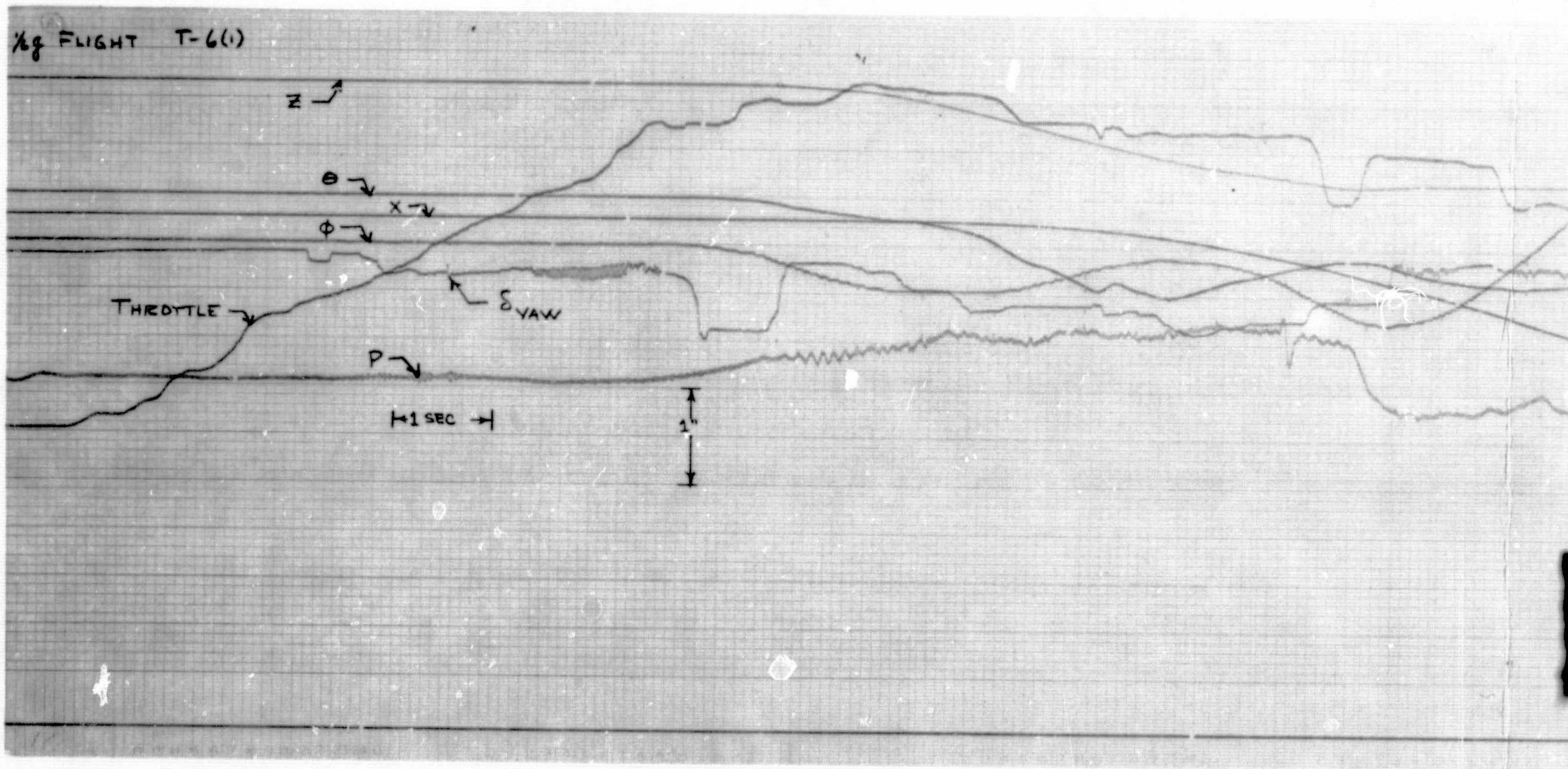

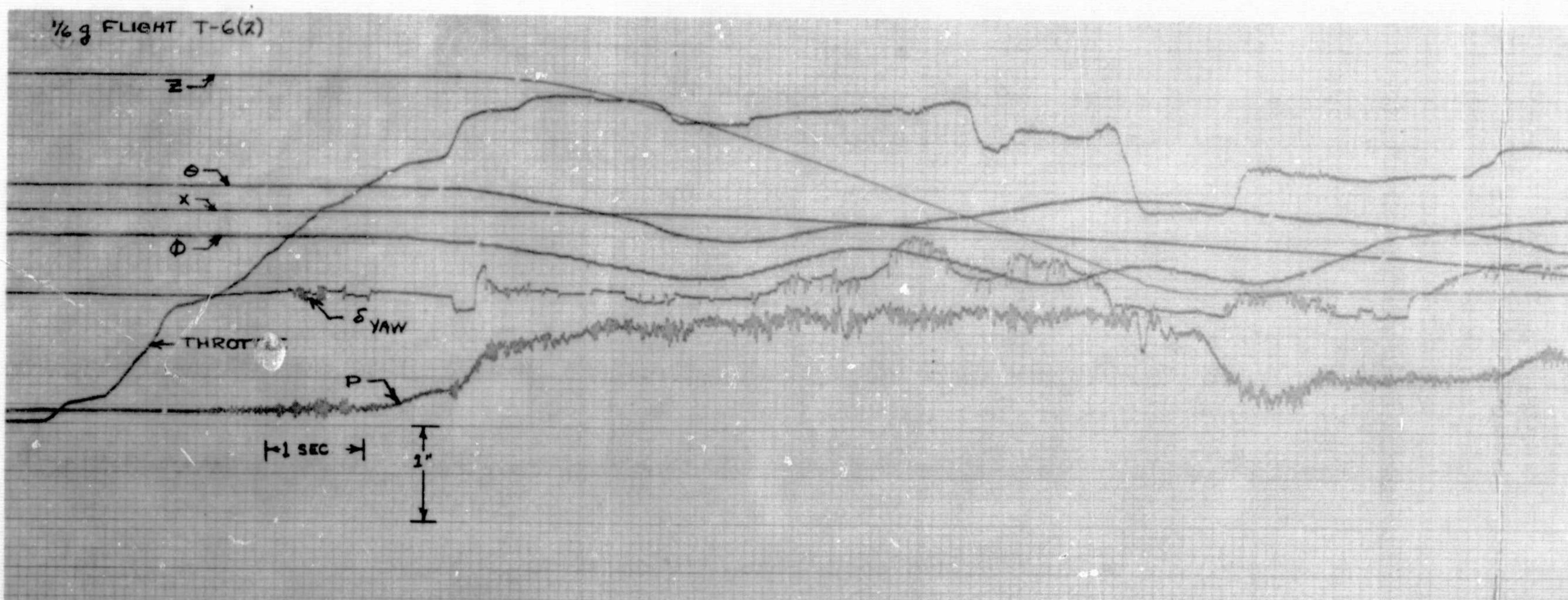

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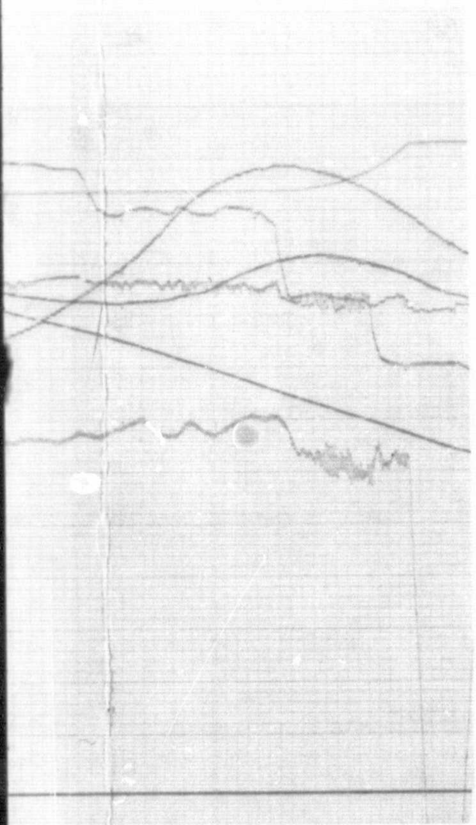

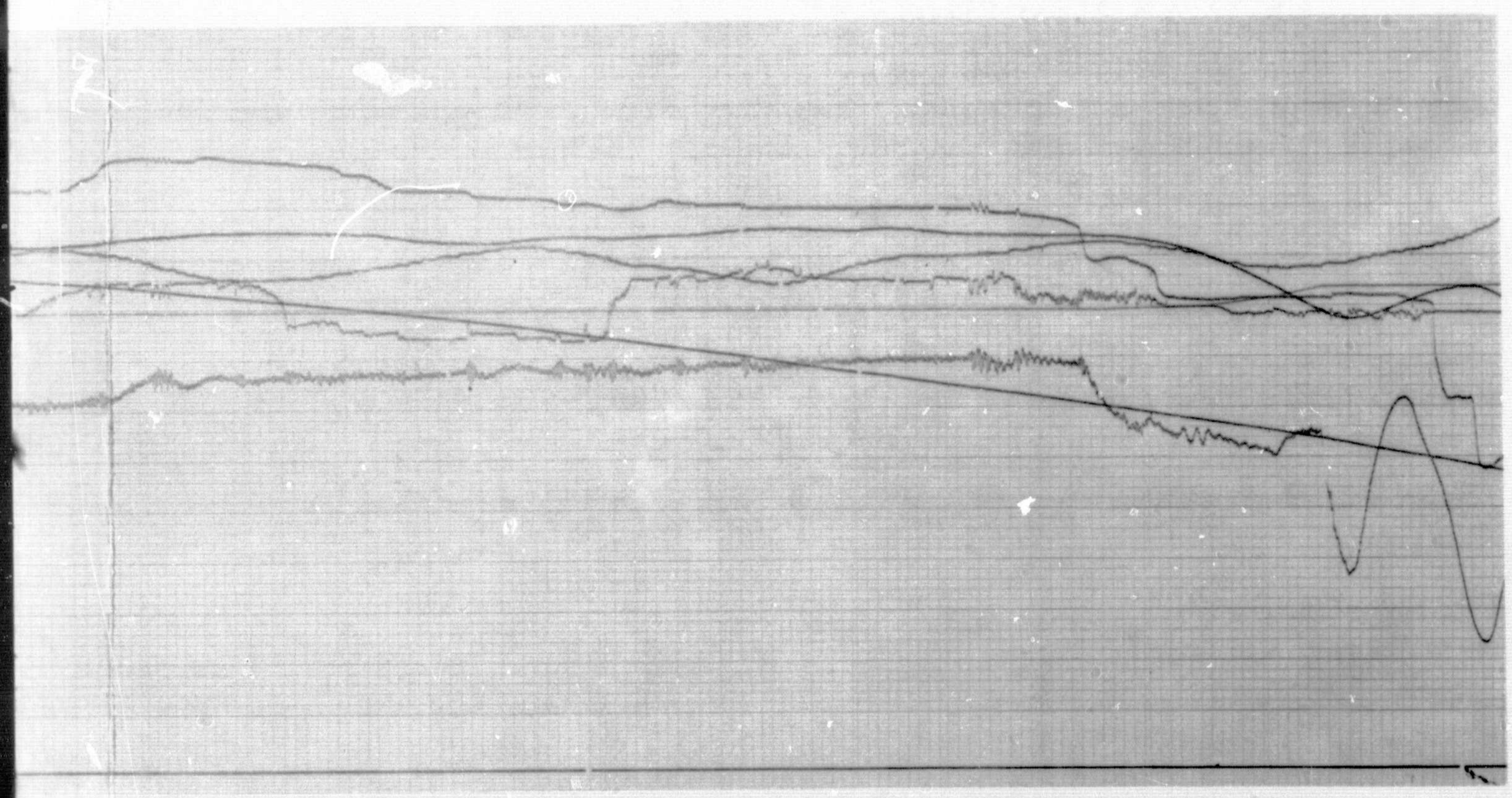

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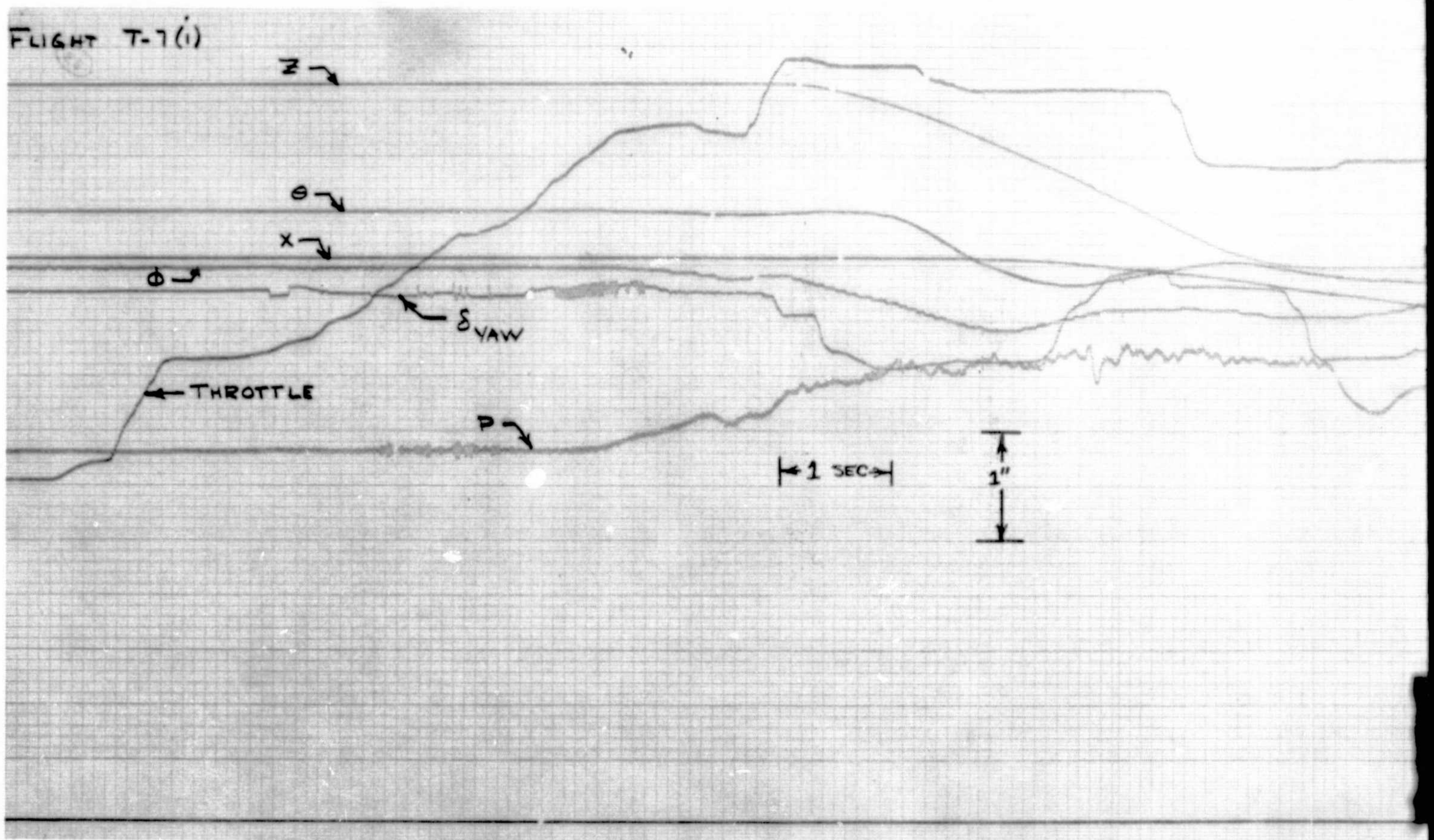
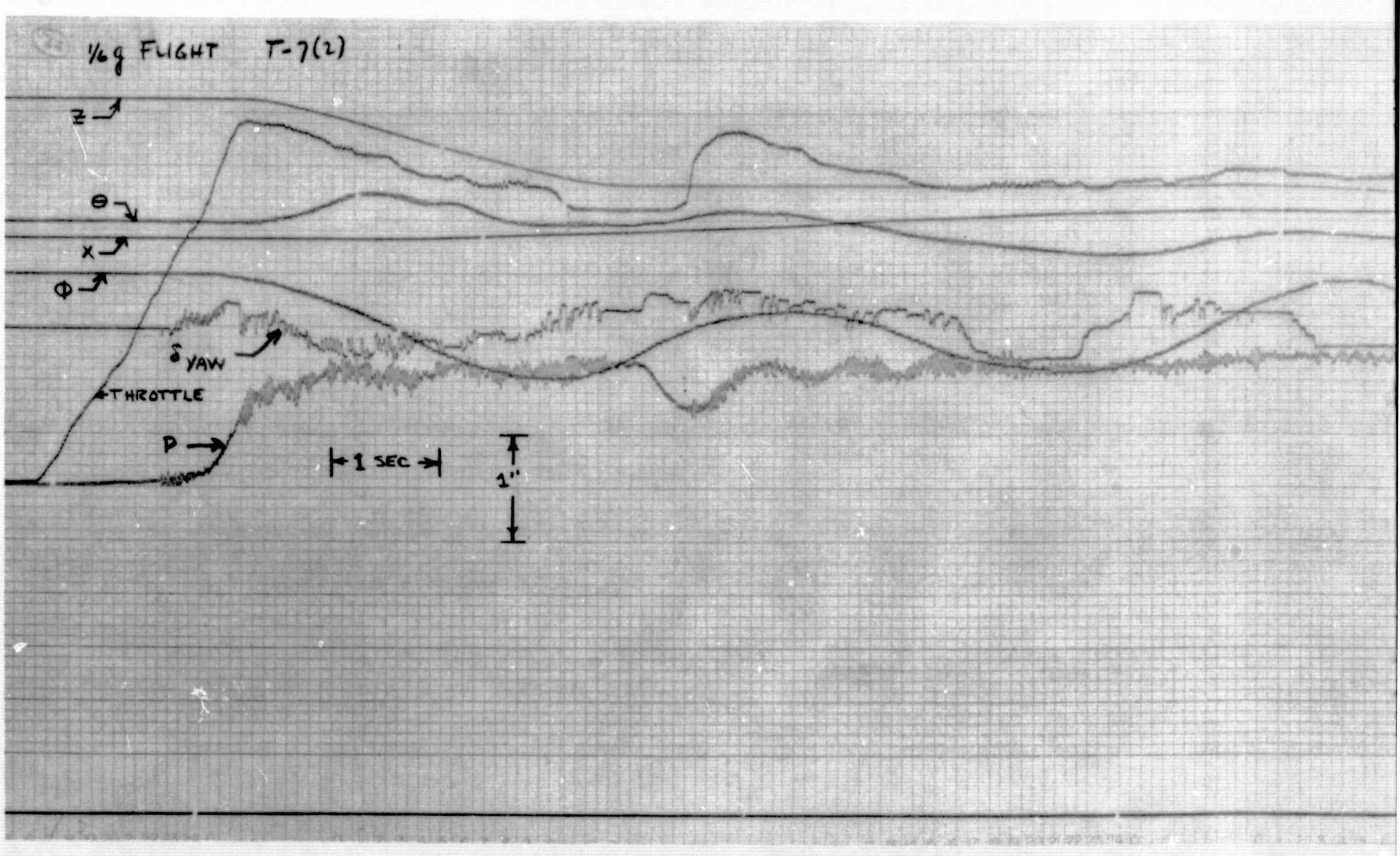
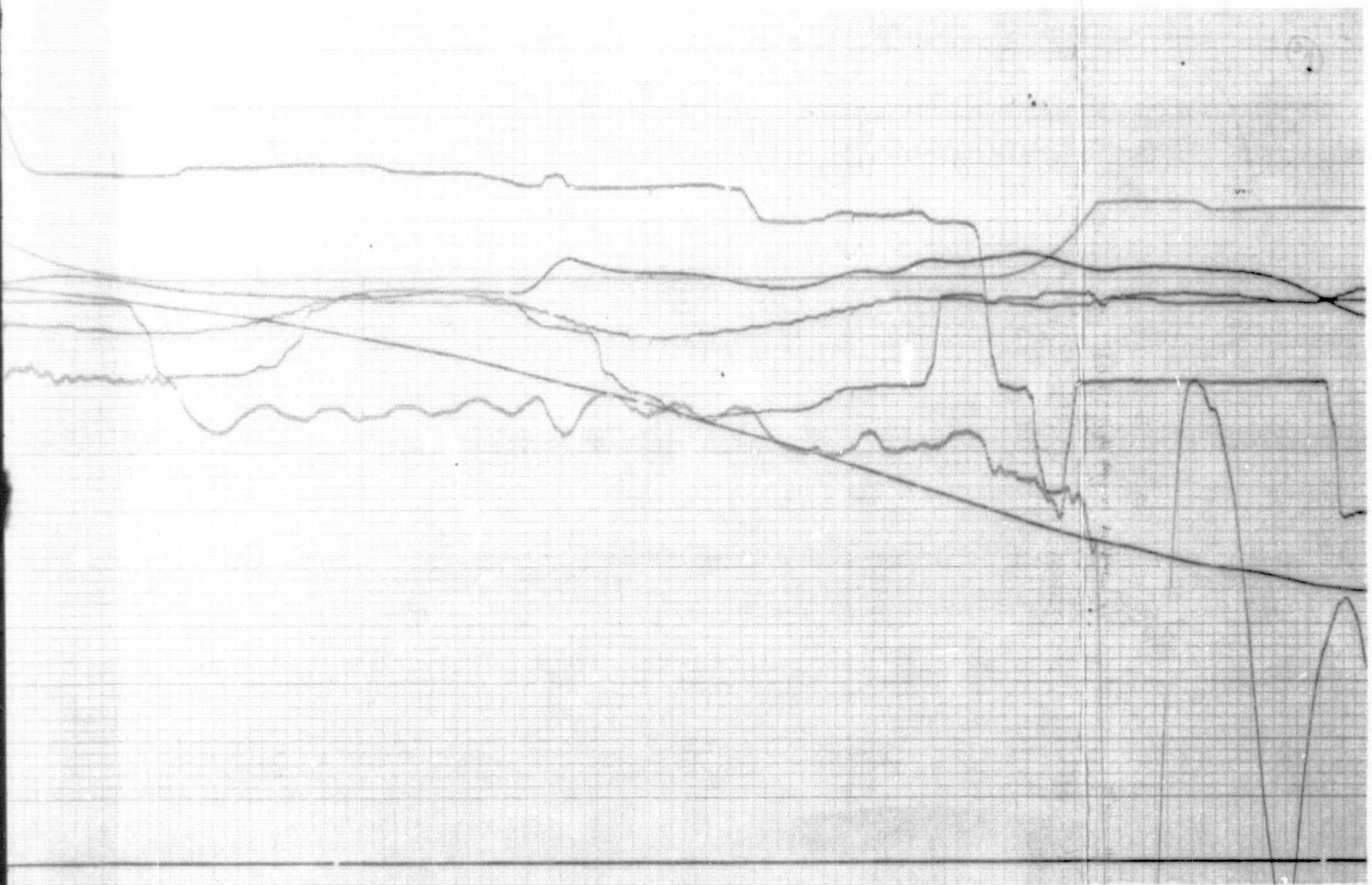
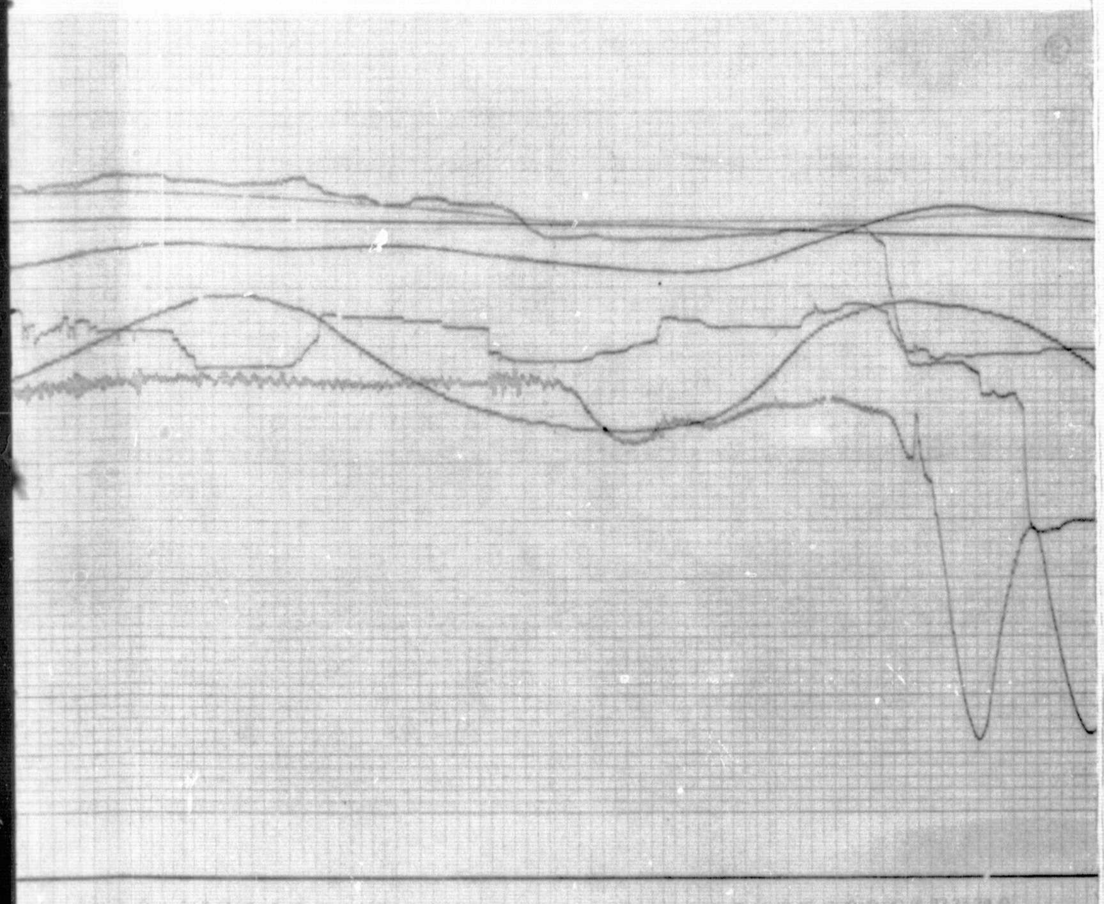
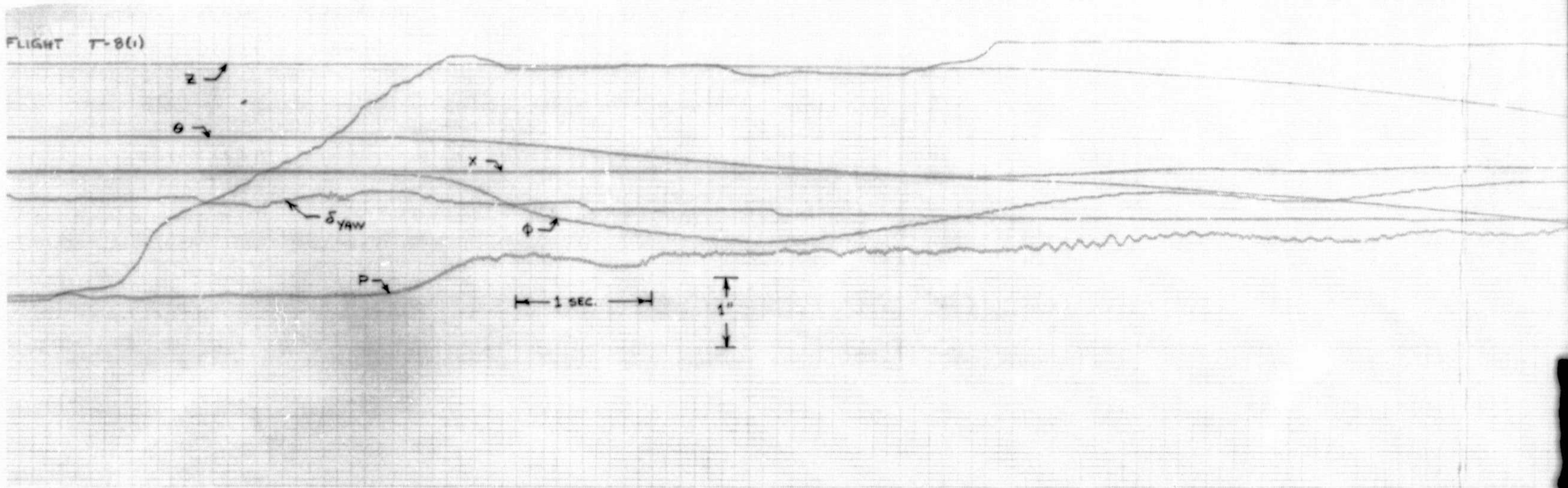
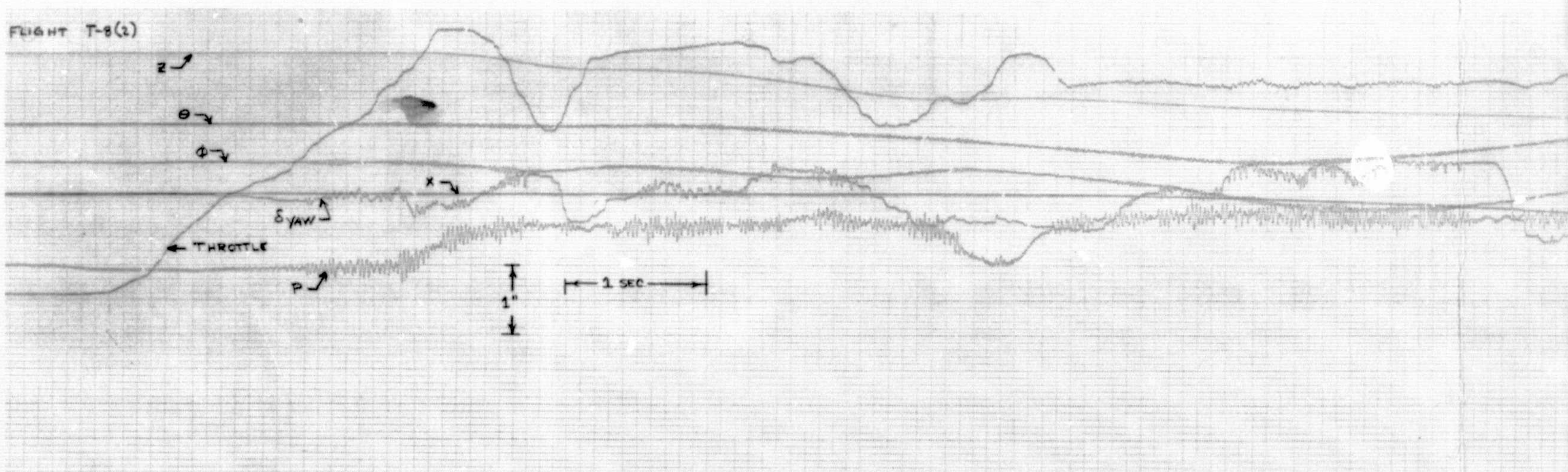

FLIGHT T-7(1)
Z
θ
X
Φ
δ YAW
THROTTLE
P
1 SEC
1"


1/6 g FLIGHT T-7(2)
Z
θ
X
Φ
δ YAW
THROTTLE
P
1 SEC
1"









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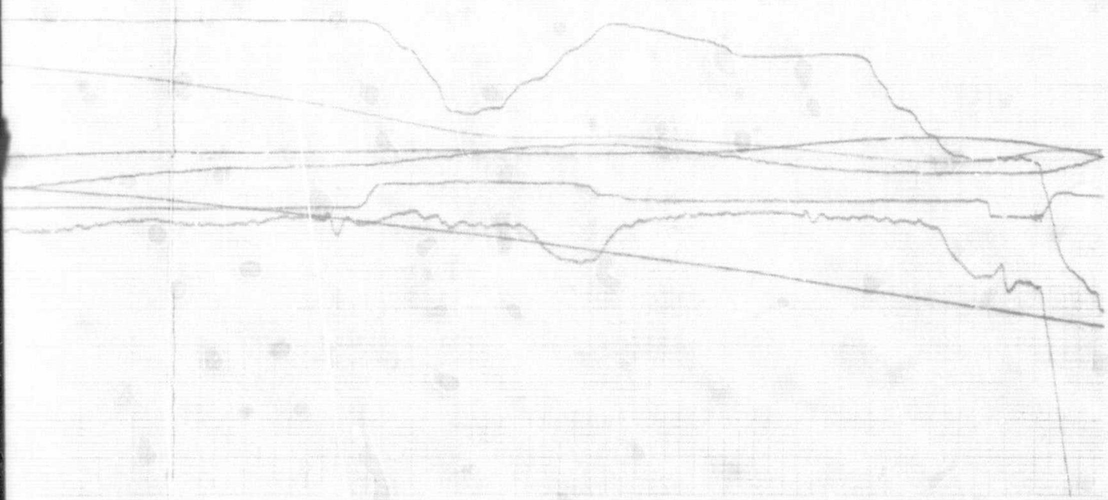

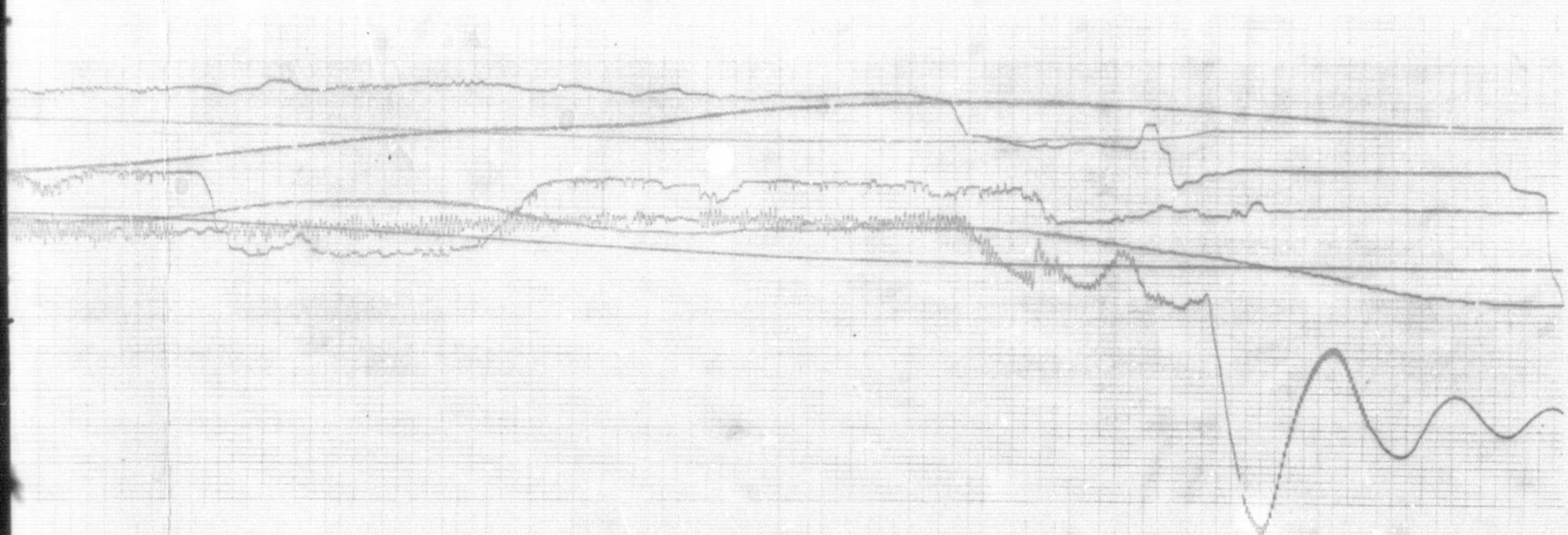

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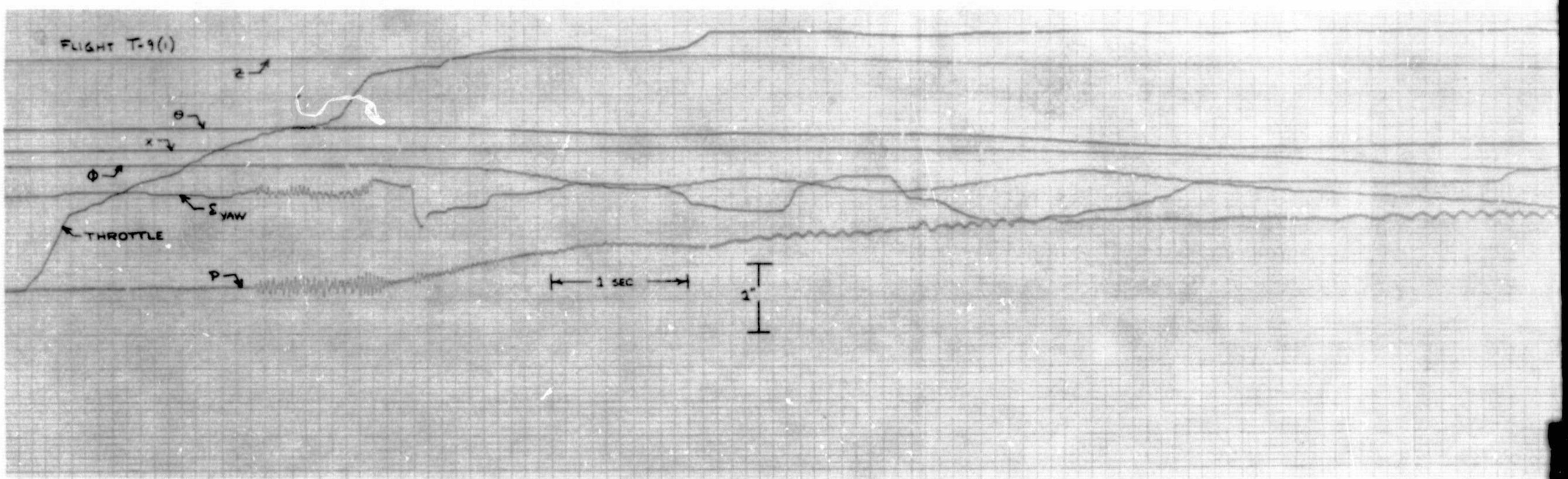

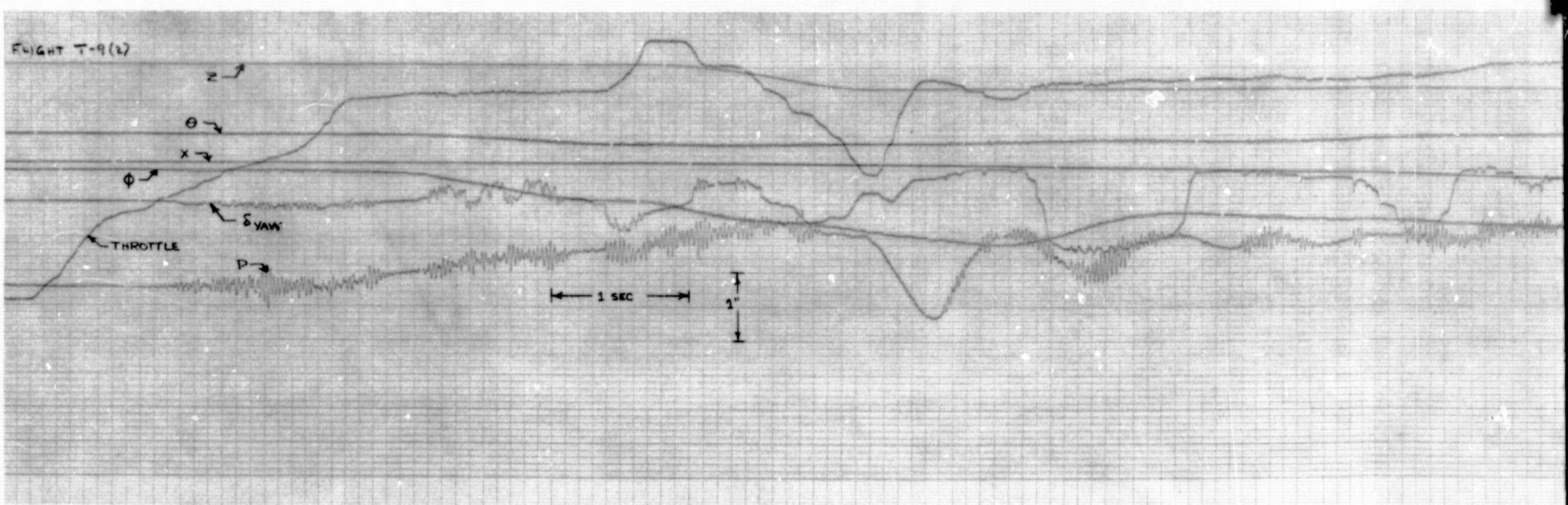

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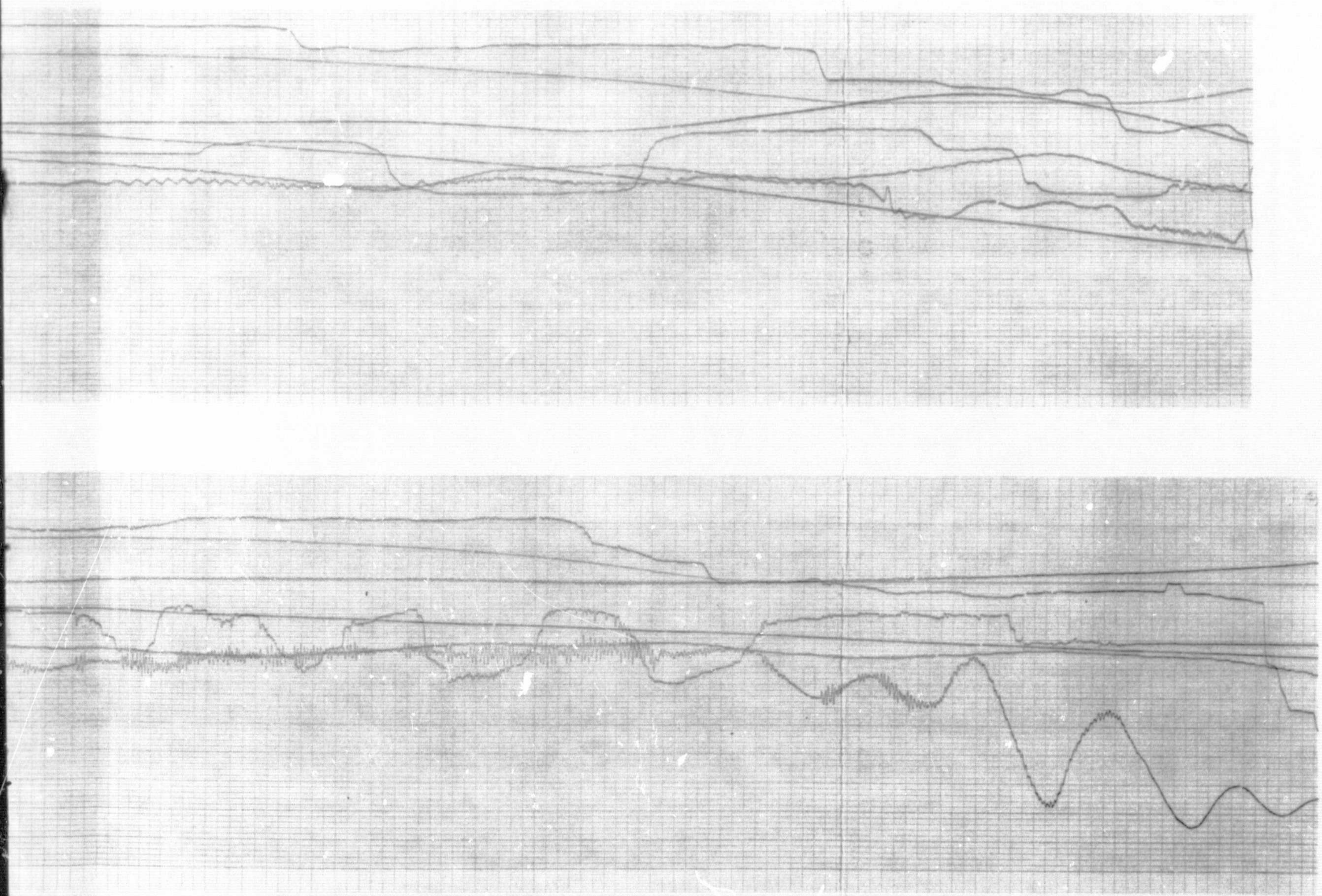

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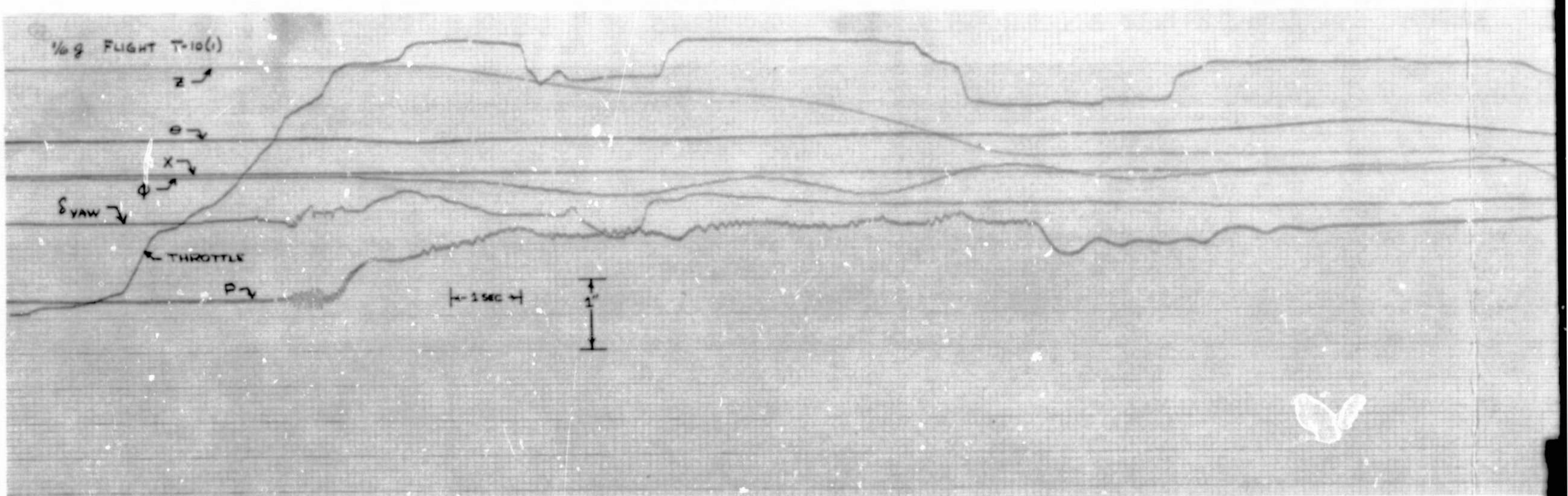

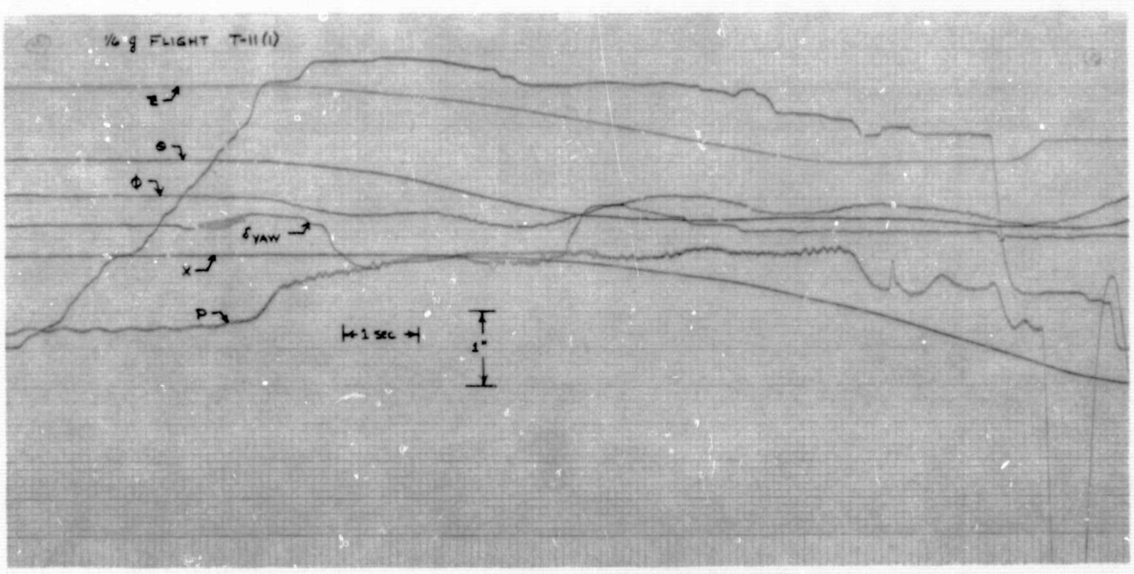

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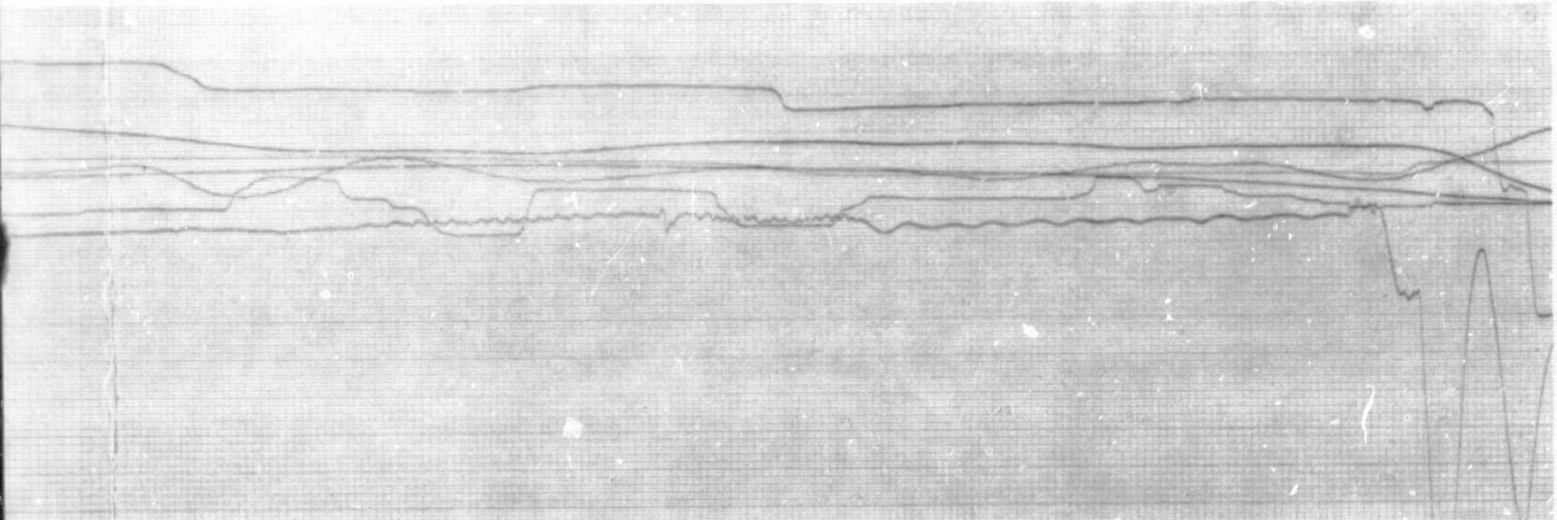

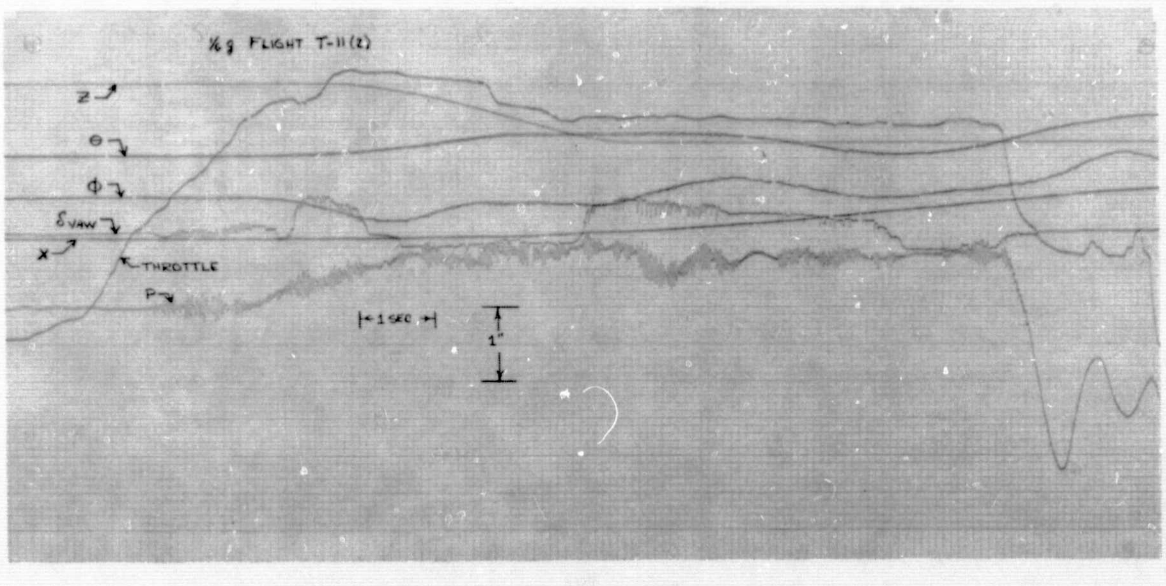

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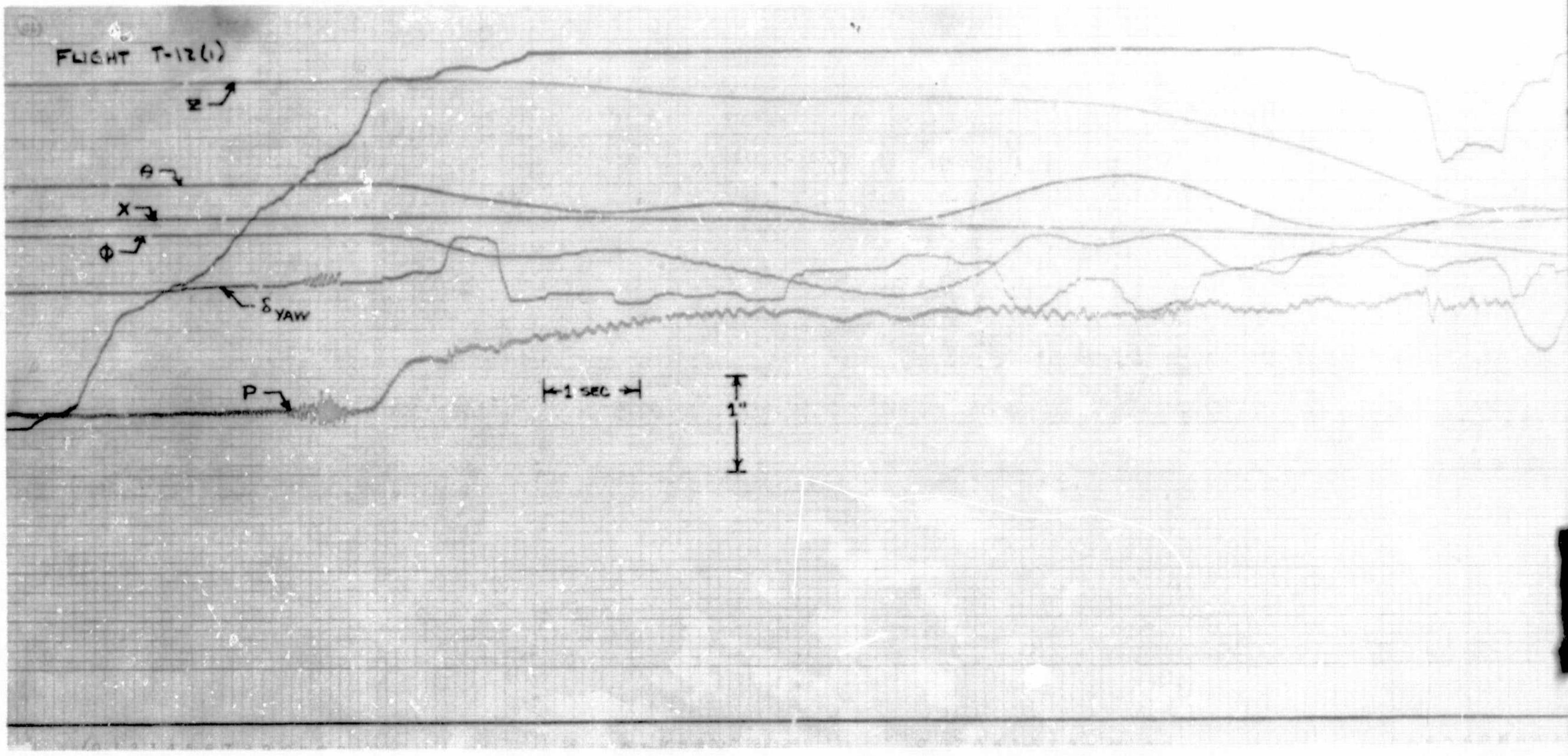
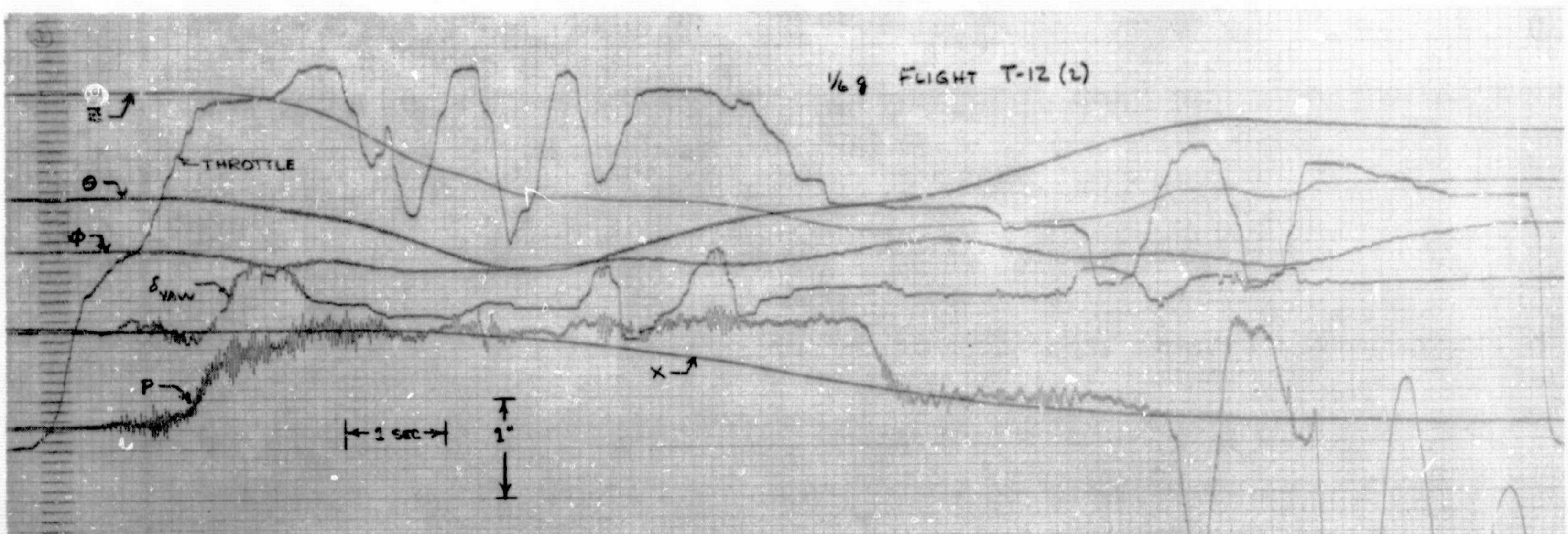
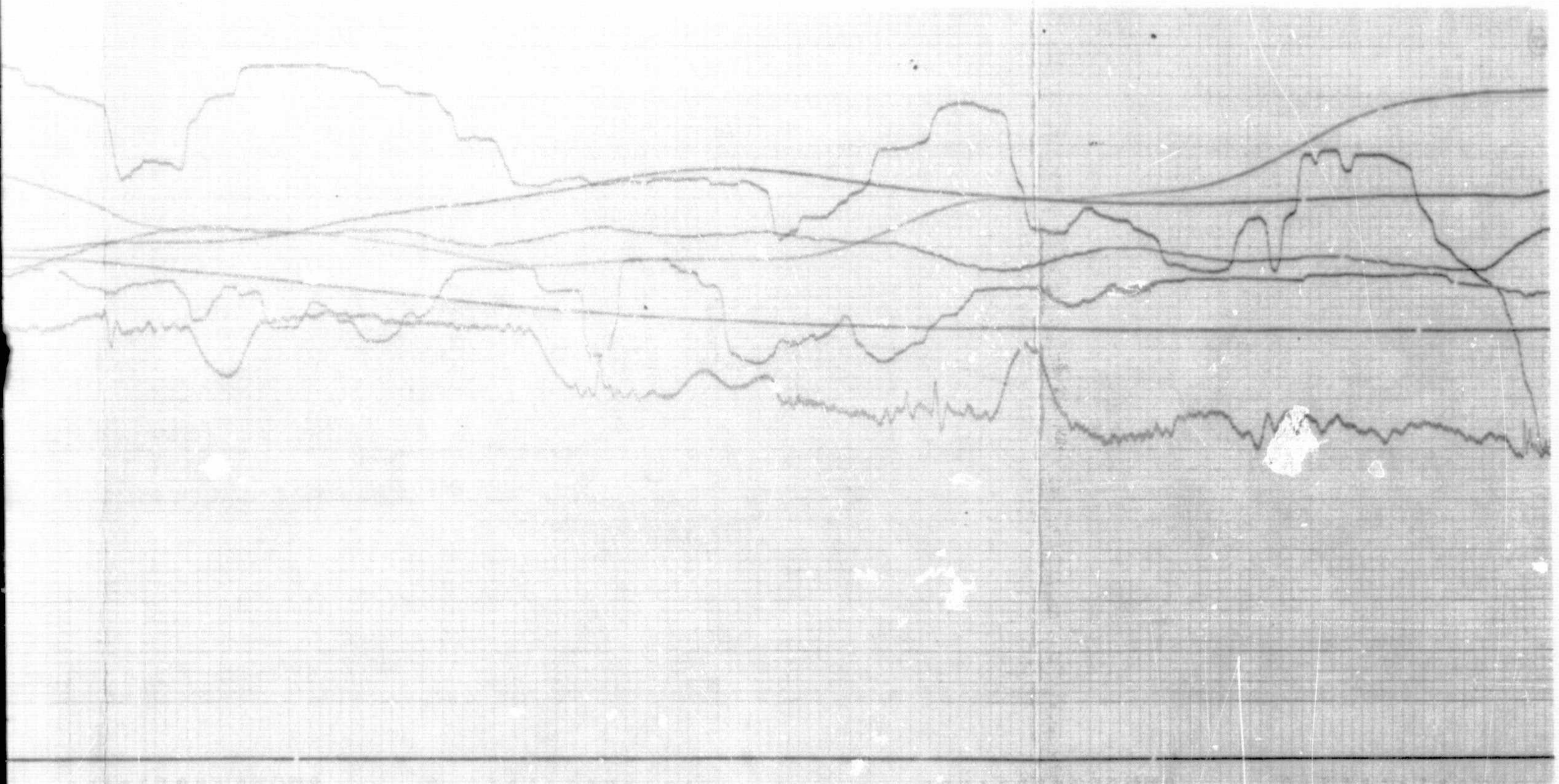
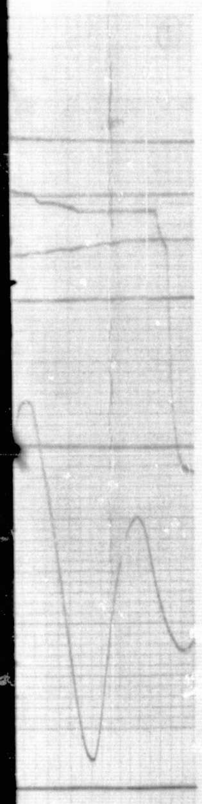

FLIGHT T-12(1)
z
θ
x
φ
δ YAW
P
1 sec
1"


1/6 g FLIGHT T-12(2)
z
THROTTLE
θ
φ
δ YAW
P
x
1 sec
1"





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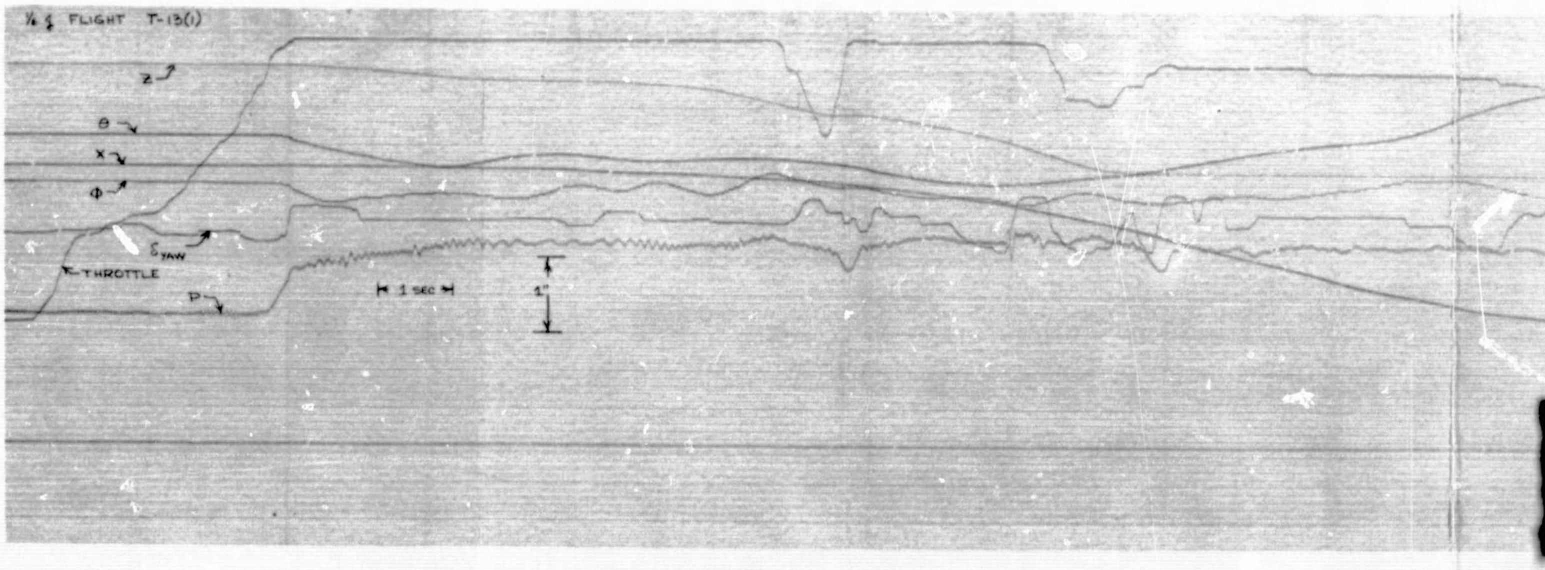

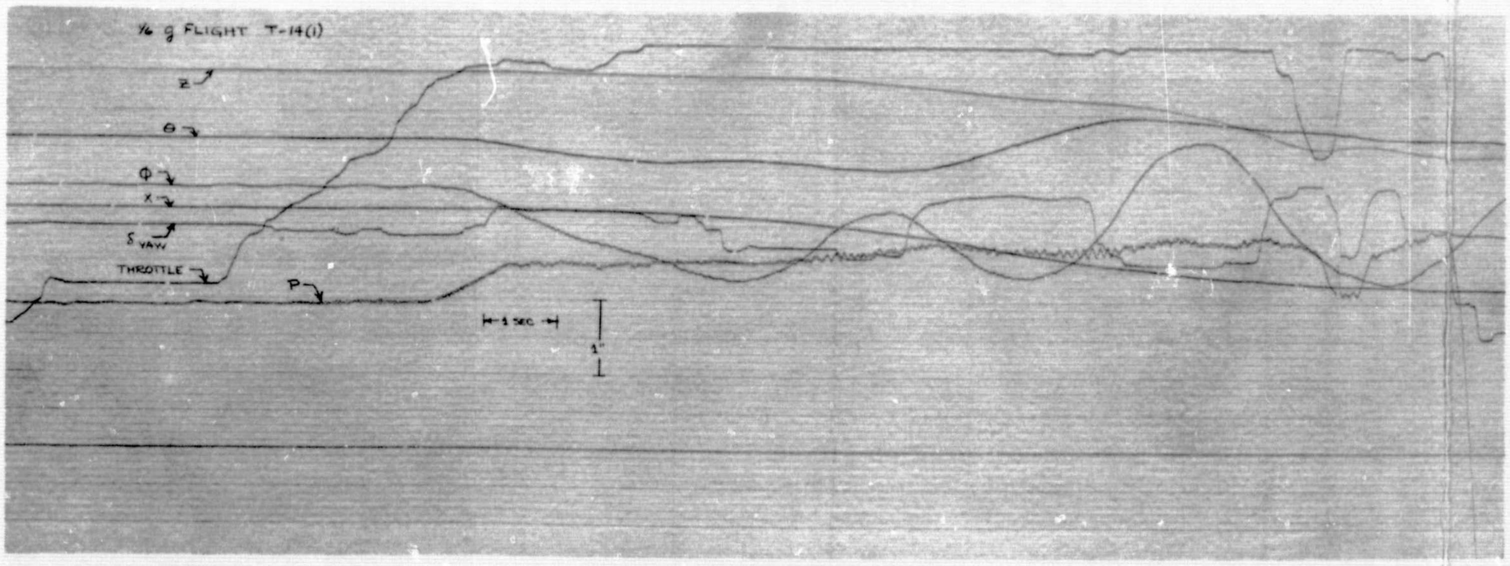

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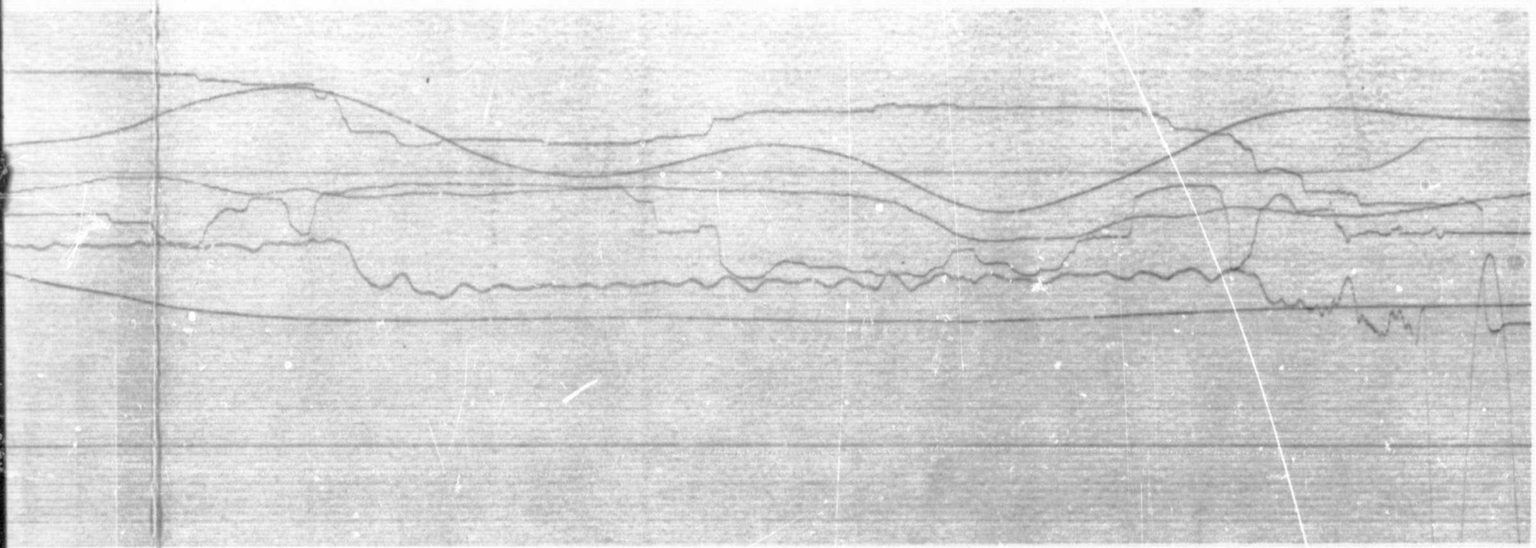

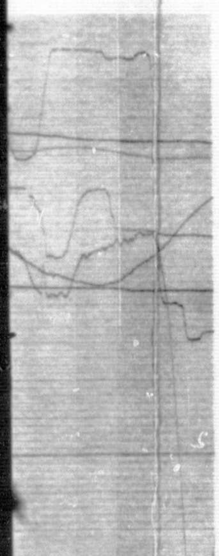

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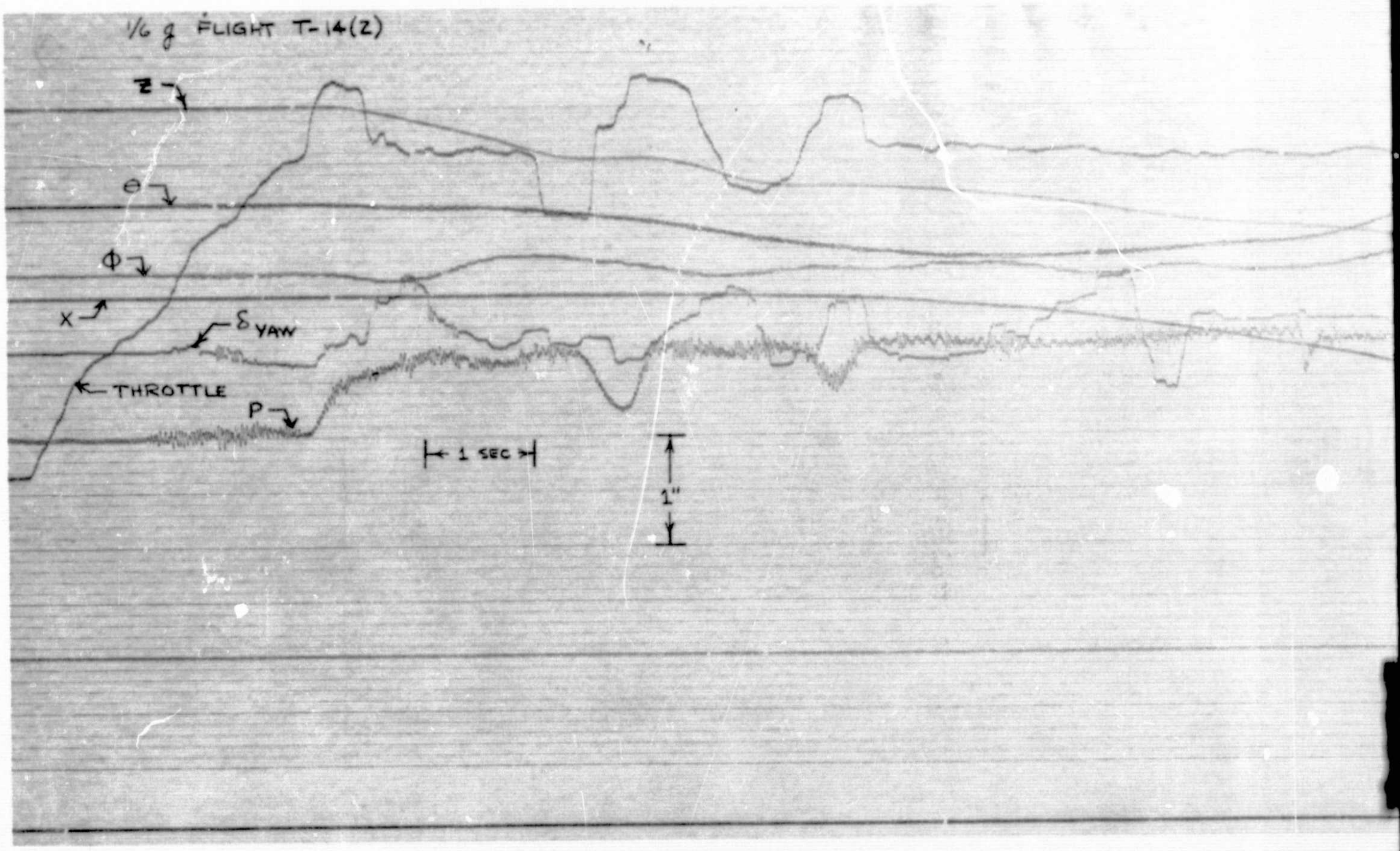

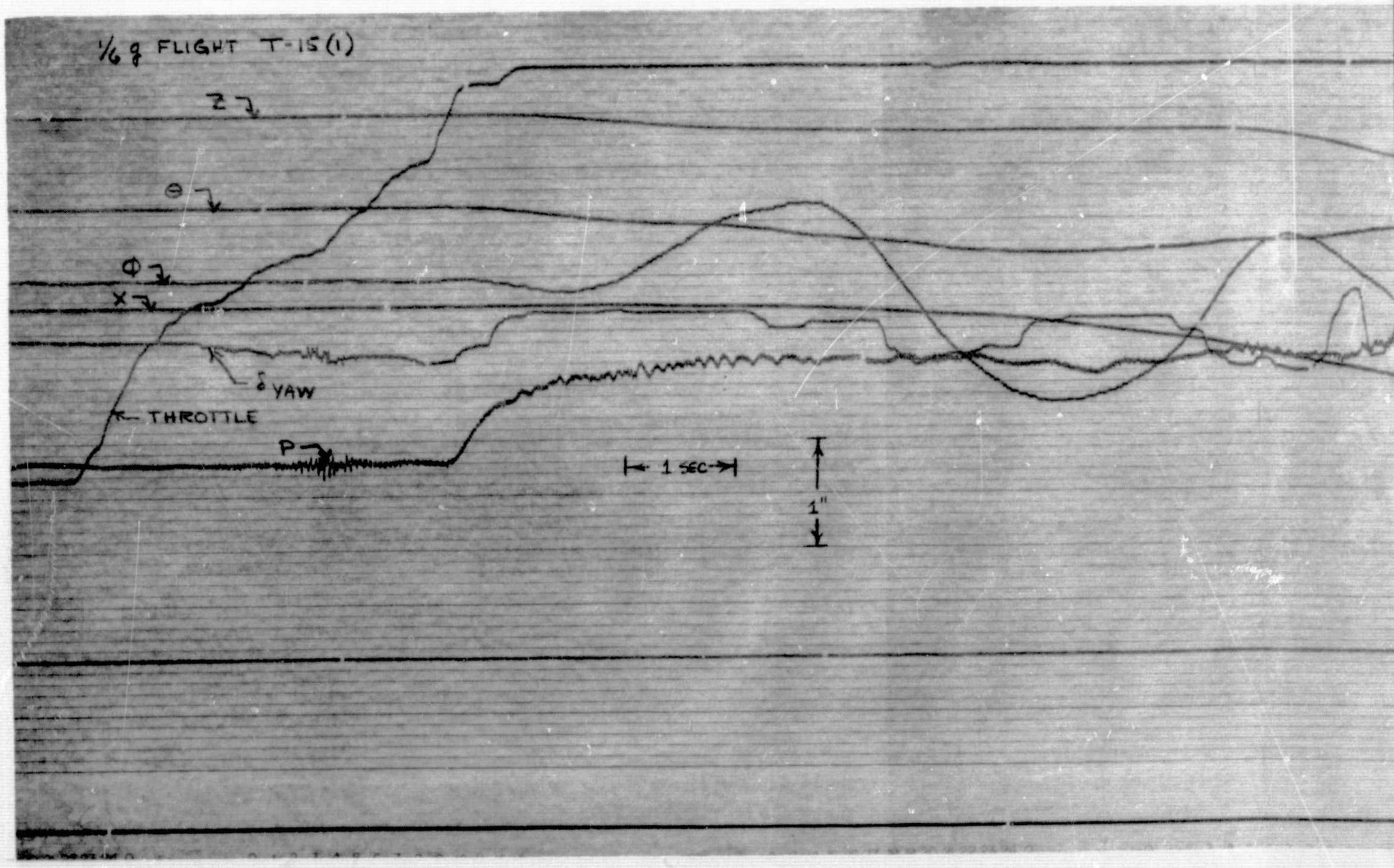

Report No. 2369-927001

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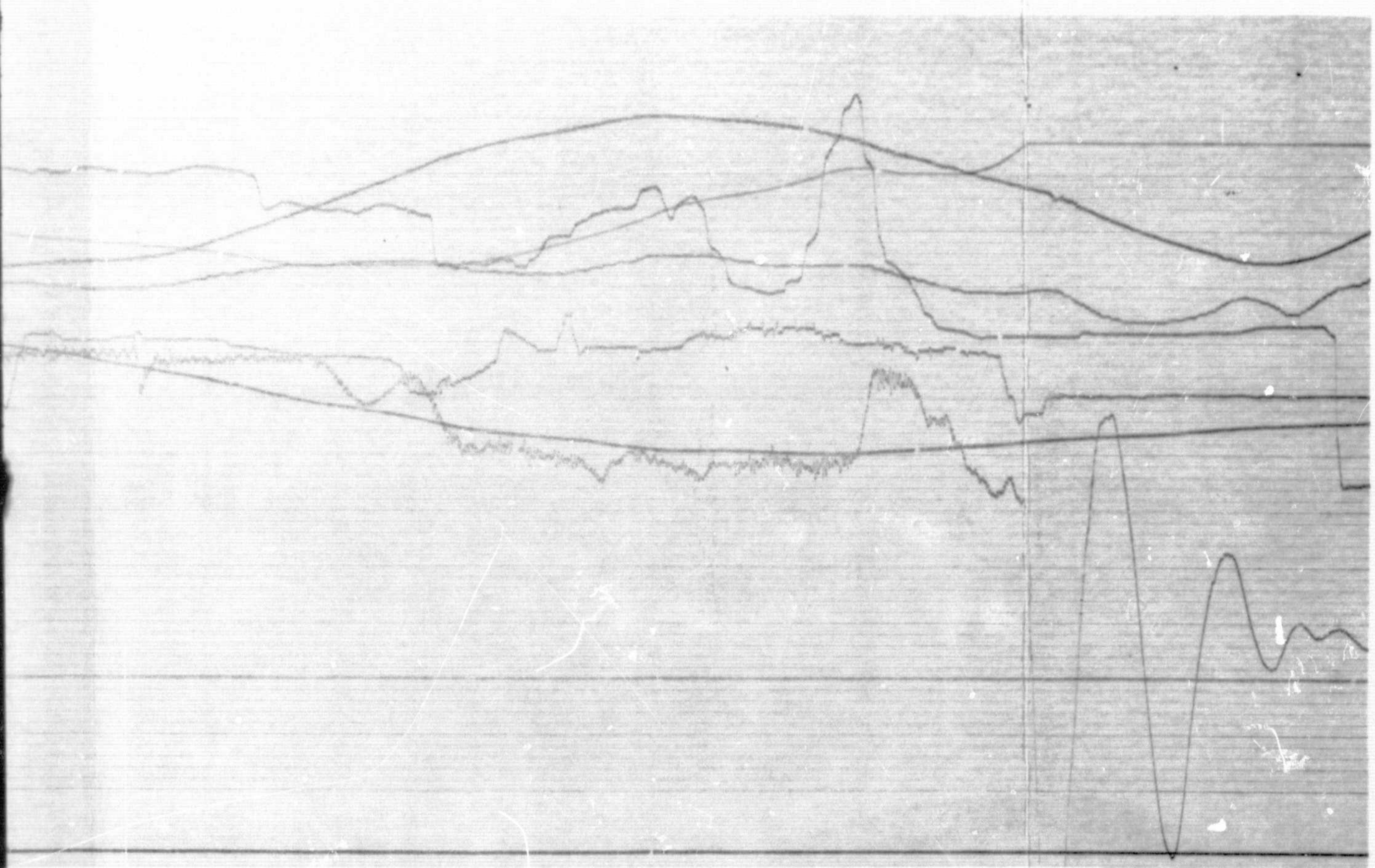
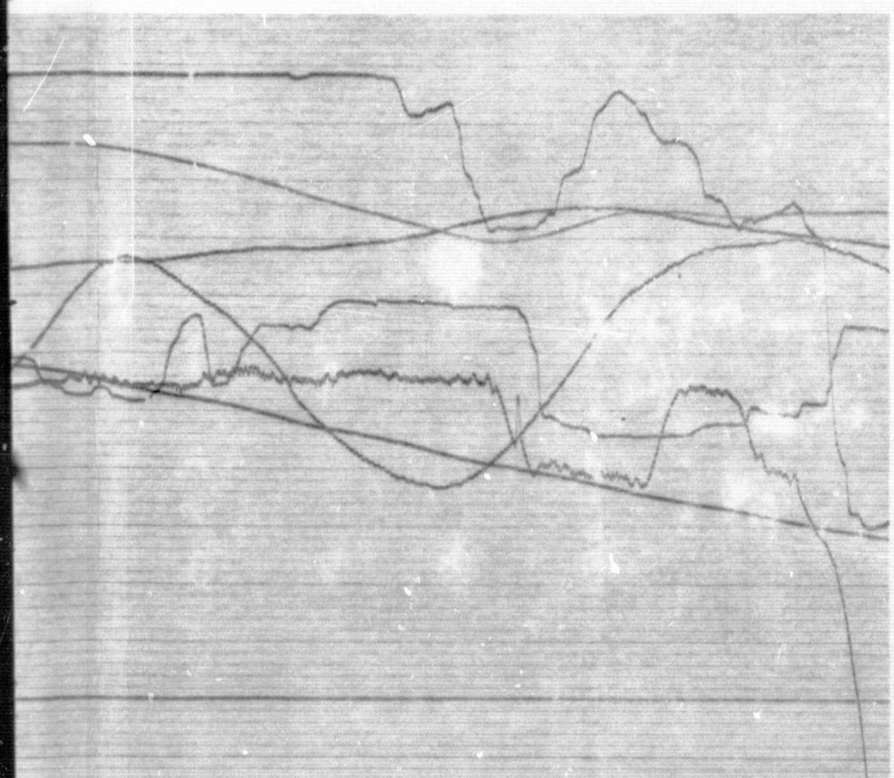
Foldout Frame





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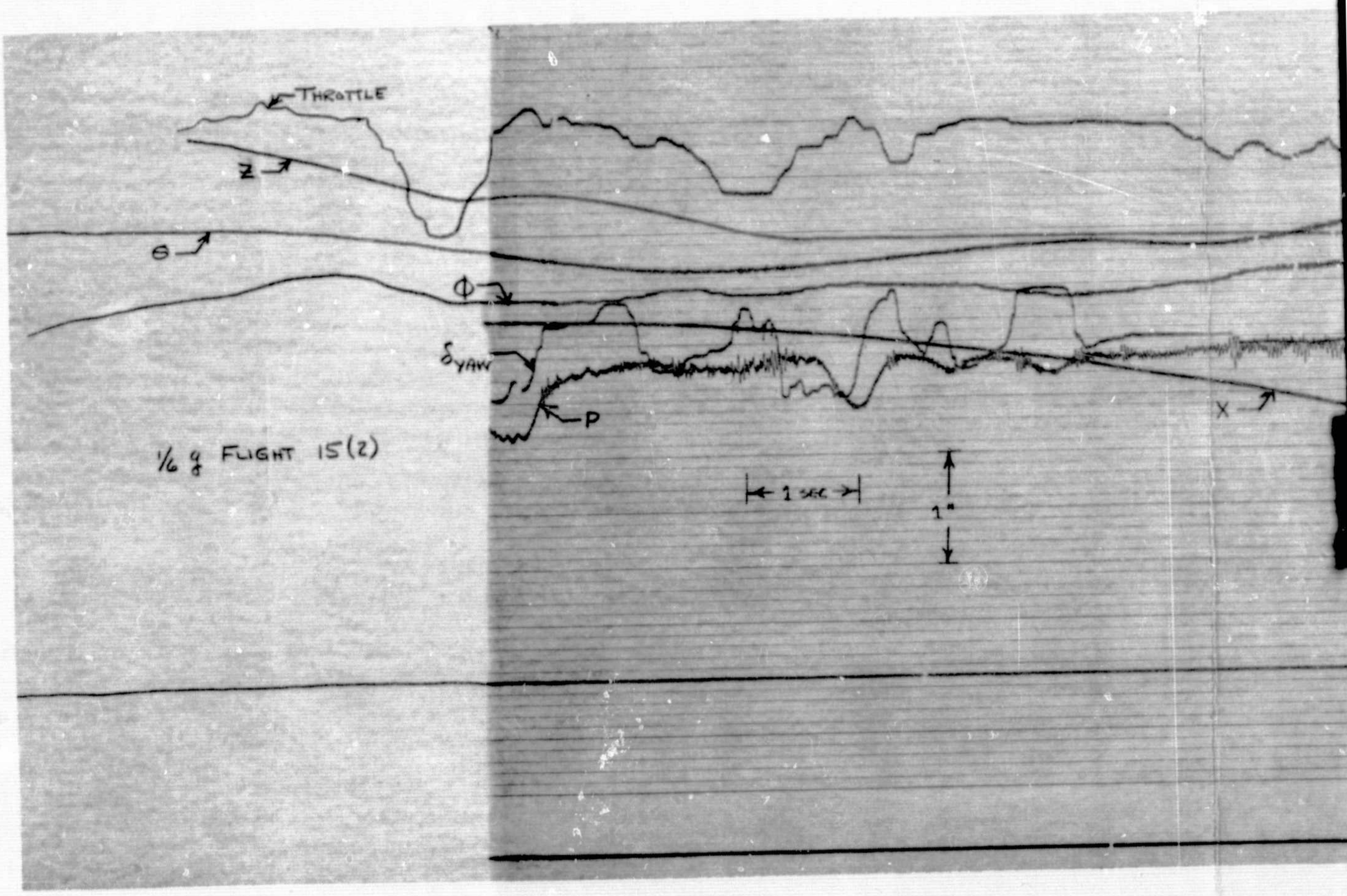

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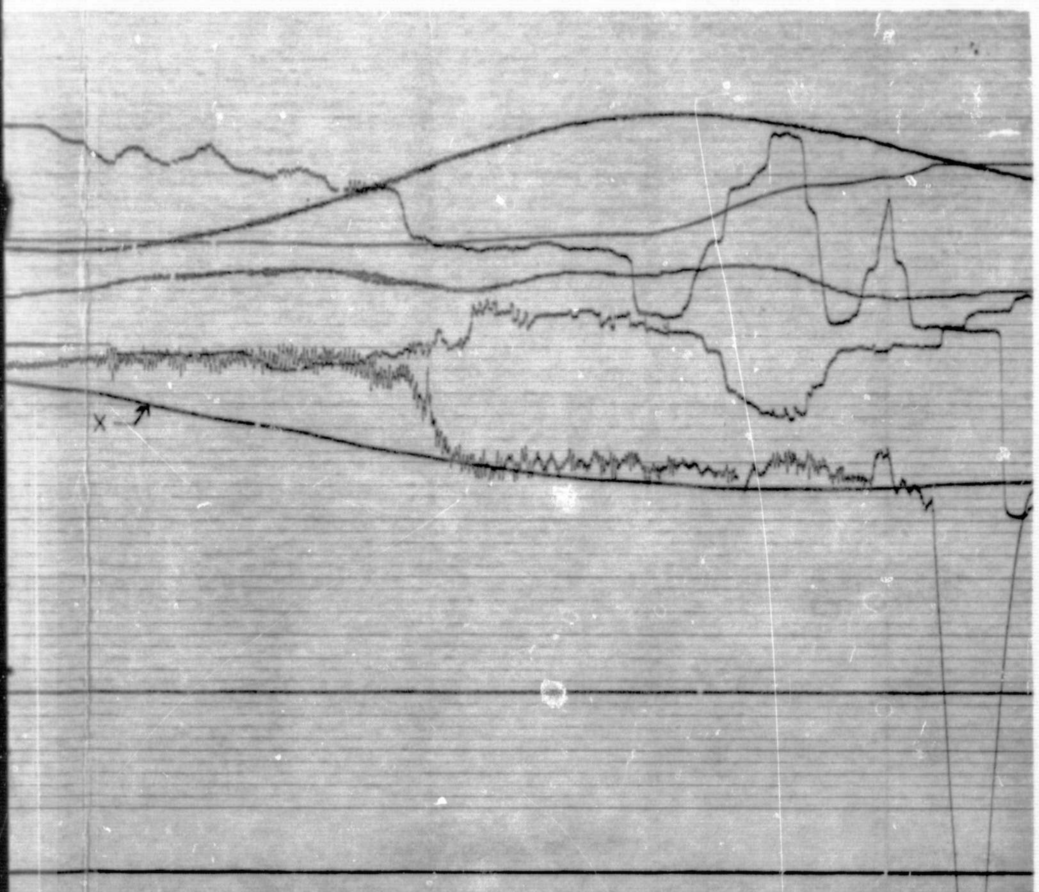

Foldout Frame #2