AN INVESTIGATION OF TERMINAL LUNAR LANDING WITH

THE LUNAR LANDING RESEARCH VEHICLE

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INTRODUCTION

Since its establishment, the Flight Research Center has been concerned with the problem of landing new types of airplanes. And, the pioneer work in reaction rockets for control of manned vehicles in a space environment was performed at this Center. Therefore, it was only natural that we should have been interested in the problem of lunar landing since it contained elements of both these areas. An inhouse study performed in the summer of 1961 disclosed that research was required in the areas shown on the first slide (slide 1-RH). To best accomplish these investigations, a simplified, inexpensive (as far as was possible), variable stability platform was proposed. It was intended to be only a research craft and, since the Apollo project was still in its conceptual stages, no attempt was made to duplicate any specific configurations. The culmination of this work was the Lunar Landing Research Vehicle. Primary features of the craft include an open tubular structure, a jet engine, as well as lift and attitude rockets.

You may ask, why not perform this research with a helicopter? The next figure (slide 2-RH) shows the comparison of translation with LEM on the moon with helicopter translation and LLRV translation on the earth. Each craft is shown to scale and the relatively small size of the LLRV is apparent. Note that translation of LEM will be accomplished by tilting the thrust vector to provide horizontal vector components in the direction of desired motion. Because of the reduced mass of the moon, the lunar gravity attracts the LEM with 1/6 the force that would be experienced on the earth. Assume a 28-degree tilt angle was commanded in LEM to acquire a desired translational acceleration. Simulating this situation on the earth, a helicopter would have to provide thrust to overcome the pull of the earth's gravity field and would tilt only 5 degrees to achieve the translational acceleration of LEM. The LLRV, however, utilizes the jet engine in a servo driven double gimbal to support 5/6 of its weight along the local vertical, thereby creating a pseudo lunar gravity field. Lift rockets fixed to the outer, tilting portion of the frame thrust equivalent to that commanded by LEM and require the LLRV to tilt to angles as large as those of LEM to achieve the proper translational acceleration. And, needless to say, the pilot experiences considerably different reaction to flying at 5 degrees and flying at 28 degrees.

BASIC INFORMATION

As you can see in the next figures (slide 3-LH and slide 4-RH), the LLRV is about 10 feet high, 23 feet long, and 14 feet wide. The pilot sits forward of the c.g. as the astronaut will in LEM. The legs are symmetrically placed 45 degrees from the orthogonal body axes. Dualized attitude rockets are displaced from the c.g. to provide control moments. Thrust of the rockets is ground adjustable between 18 and 90 pounds, each. Jet fuel tanks are located equal distances fore and aft of the engine and fuel is used equally from each tank. Two normal and six emergency lift rockets are placed about the outer gimbal rings and must be fired in pairs. Each rocket is throttleable between 100 and 500 pounds thrust. The emergency rockets have sufficient thrust to recover the vehicle in case the jet engine should fail. The jet engine, at the vehicle c.g., is a CF-700-2V engine and is a fan version of the J-85. It develops 4420 pounds thrust under standard conditions. Hydraulic actuators position the gimbals upon command from the electronics. Spheres to the right and left of the jet engine contain 90 percent hydrogen peroxide which is the fuel for the lift and attitude rockets. Two tanks to the rear of the craft hold helium for pressurizing the rocket system. Air-oil shock struts attenuate vertical impact energy and rubber shock mounts absorb horizontal touchdown energy. The aft platform contains the electronic packages and counterbalances the weight of the pilot platform on the forward end. On this platform is the variable stability system, a radar altimeter, a doppler radar, and an 80-channel PCM telemetry system.

Vehicle weight (slide 5-RH) is 3925 pounds and is distributed as you see on the figure. Preflight jet engine idling and rocket system checks consume approximately 150 pounds, so lift-off weights run about 3775 pounds. There is enough jet fuel aboard for 10 minutes of flight and enough rocket fuel for about two minutes of lunar simulation time.

The vehicle takes off, climbs to altitude, and gets set up for the simulation on the jet engine alone. Jet engine performance in terms of altitude is shown on the next slide (slide 6-RH). As can be seen, jet engine performance is highly dependent on air temperature and pressure. Here at Edwards on a standard day the vehicle can climb to 4000 feet. With an increase of 20 degrees in temperature -- the warm day curve -- this altitude is reduced to 1000 feet. But this is adequate to accomplish the desired simulation.

CONTROL SYSTEM

(Slide 7-LH) A large share of the electronics on the LLRV is required to make the simulation possible. An auto-throttle maintains the jet engine thrust at a level to counteract 5/6 of the vehicle weight. The jet engine is held vertically as the craft tips by a servo position system and tilts small amounts from the vertical to counteract aerodynamic forces as can be seen in the figure. These systems are basically acceleration systems. The next slide (slide 8-RH) presents a time history of system parameters while in the lunar simulation mode. Here the craft is translated forward while descending to touchdown. Since winds were calm this day, the engine and vehicle angles are seen to nearly coincide. The command and sensed accelerations agree to within 0.03 g. System touchdown transients are barely perceptable to the pilot at impact when engine attitude reference is switched to local vertical, exclusively.

A greatly simplified block diagram of the attitude control system is shown on the next figure (slide 9-RH). As can be seen, stick sensitivity, threshold and hysterisis, control power, rate feedback and angle feedback can all be changed independently. Only the stick sensitivity can be varied in flight, however. With two independent sets of rockets and electronics on board, one set is always kept at a known, satisfactory level while the other is varied. That way, if the test condition is unsatisfactory, the pilot can always switch to the other set. Control power capability of the various modes is shown on the next slide (slide 10-RH). Most of the testing to date has been in the lower control power regions to approximate LEM values. All flights have been made in a rate command mode, but flights in the future will examine the angle and acceleration command modes as well. Up to now, a center stick and pedals have been used, but a 3-axis side arm controller will be installed shortly for all remaining tests. Rate deadbands of from 0.5 to 2 deg/sec have been used. An extensive analog simulation of LLRV handling qualities has been performed. The following slide (slide 11-RH) shows pilot ratings on a Cooper rating scale for the pitch mode during maneuvering tasks. For these data the system is providing rate command with a 2 deg/sec deadband. The boundaries defining the satisfactory area are based on the simulator tests. The flight ratings generally agree with the simulator data although the ratings do become less favorable as control power is reduced.

DISPLAY

The pilot display panel for LEM had not been designed when the LLRV was being fabricated. Therefore, the LLRV pilot panel was designed at the Flight Research Center (slide 12-LR). A thrust-to-weight meter, a rate of climb and dive meter, an altimeter, and a horizontal velocity meter were designed and fabricated in-house. In addition, a three-axis ball, jet engine instruments, rocket system instruments and a strip of annunciator lights were incorporated into the panel shown on the slide. However, now that the LEM design has been better defined, work is underway to update the LLRV cockpit and make it more like that of LEM (slide 13-RH). The cockpit in this slide is the cockpit associated with the LLRV analog simulation. In this configuration, the instrument panel has been moved to the right hand corner of the cockpit; the three-axis attitude controller has been added to the right of the seat; and a side controller has been added on the left side for controlling lift rocket thrust. As soon as tests are completed in the simulator to the satisfaction of the pilots, the LLRV cockpit will be modified. Also, plans call for masking the LLRV cockpit to provide the pilot with visibility equivalent to that of LEM.

TRAJECTORIES

Particularly in the research of maneuvering flight the LLRV has and will continue to contribute valuable information. The next slide shows a representative LLRV simulation of a LEM trajectory (slide 14-RH). As was mentioned earlier, the LLRV takes off on the jet engine alone and accelerates to the point of intersection with the LEM trajectory. At this point the lunar simulation system is engaged and the LLRV duplicates the terminal lunar trajectory. The exact conditions for this trajectory are a point for research. Lunar thrust-to-weight ratios of up to 2 lunar g's can be simulated. Tilt angles up to 30 degrees can and have been used to effect and stop translation. Circling approaches in addition to straight-in approaches already examined, will be considered. The effect of display and visibility on the types of patterns used will be examined.

Finally, on each flight the touchdown will draw great interest. The ability of the pilot to touchdown softly and evenly is of concern because of the greater tendency to tip-over in the lowered, lunar gravity field. So far, vertical velocities at touchdown have not exceeded 3 fps and horizontal velocities have not exceeded 2 fps at touchdown.

SUMMARY

In summary, the LLRV has made 43 flights totaling 2 1/2 hours of flight time. Two pilots have shared the flying. The first 10 flights checked out the vehicle attitude control system. The next 7 checked out the auto-throttle. The next 17 checked out the total lunar simulation system. The most recent flights have been devoted to the attitude control system and handling quality research. With appropriate LEM control, display, and visibility conditions, the trajectory work will be performed. It is anticipated the program at the Flight Research Center will be completed next summer.

With this background we can proceed to the next paper which will discuss, from a piloting standpoint, some results obtained with the craft at this time.

RESEARCH OBJECTIVES

ATTITUDE CONTROL

MANEUVERING

HANDLING QUALITIES

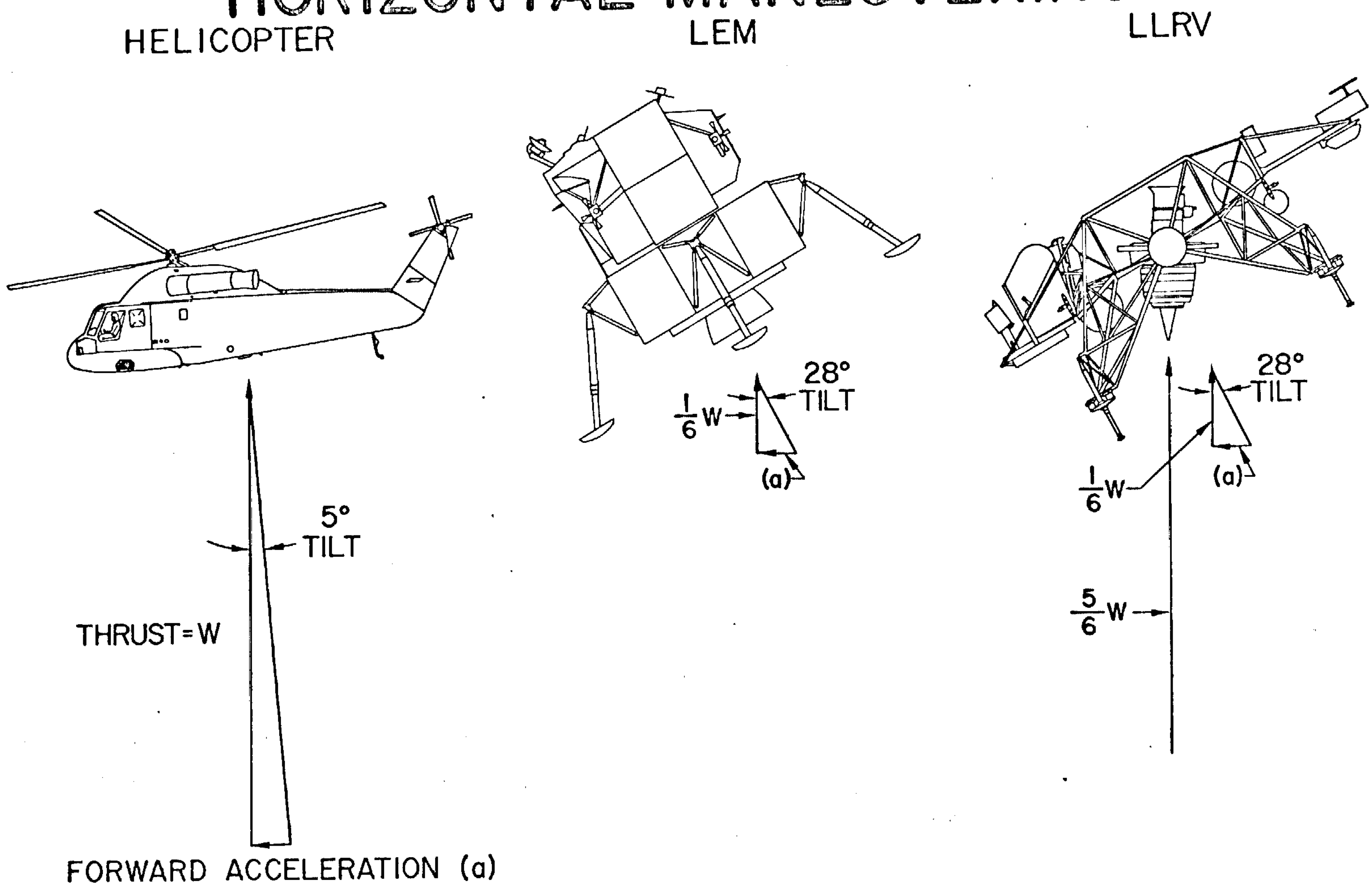
DISPLAY

VISIBILITY

Slide 1

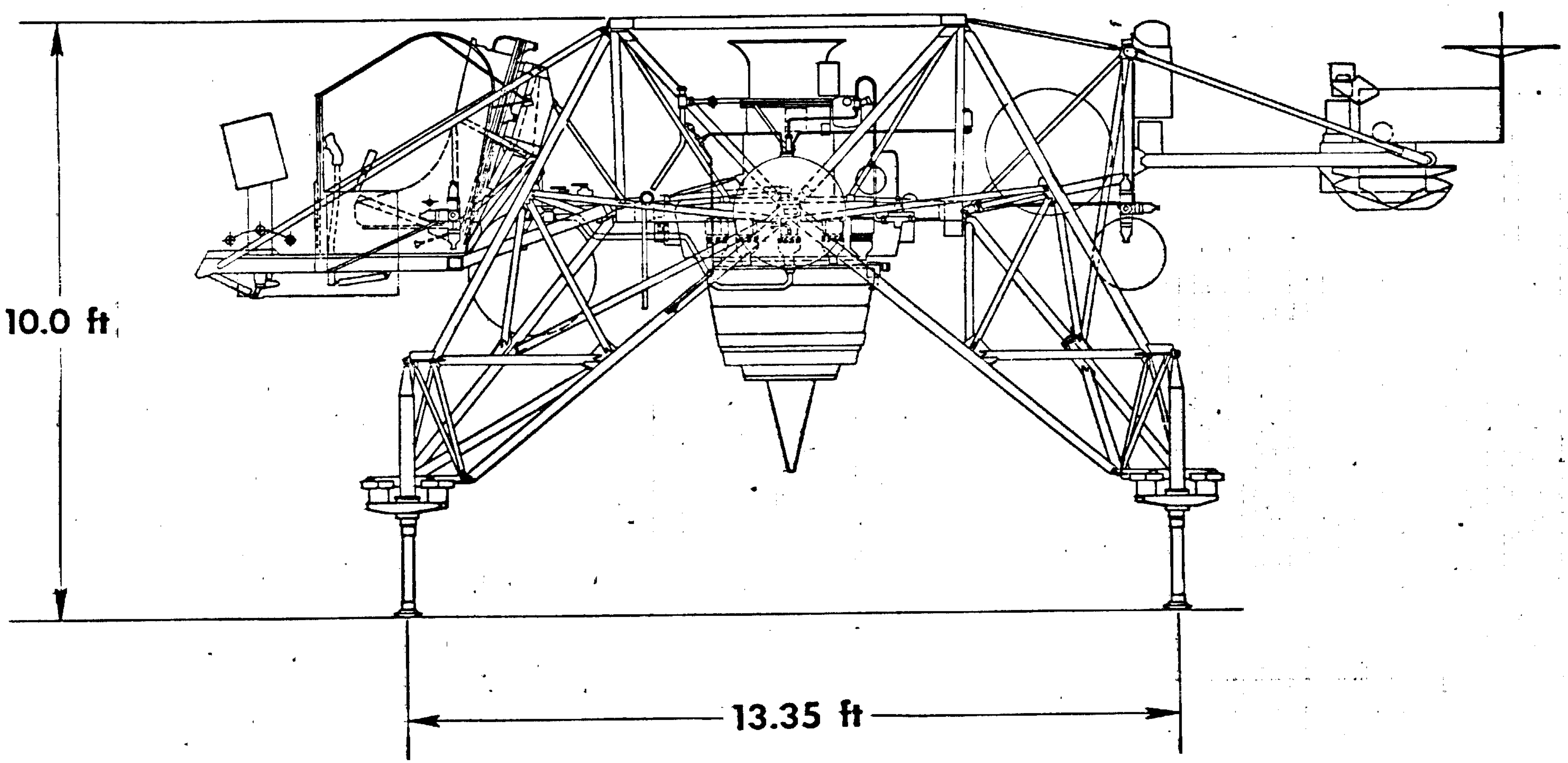
2060

HORIZONTAL MANEUVERING



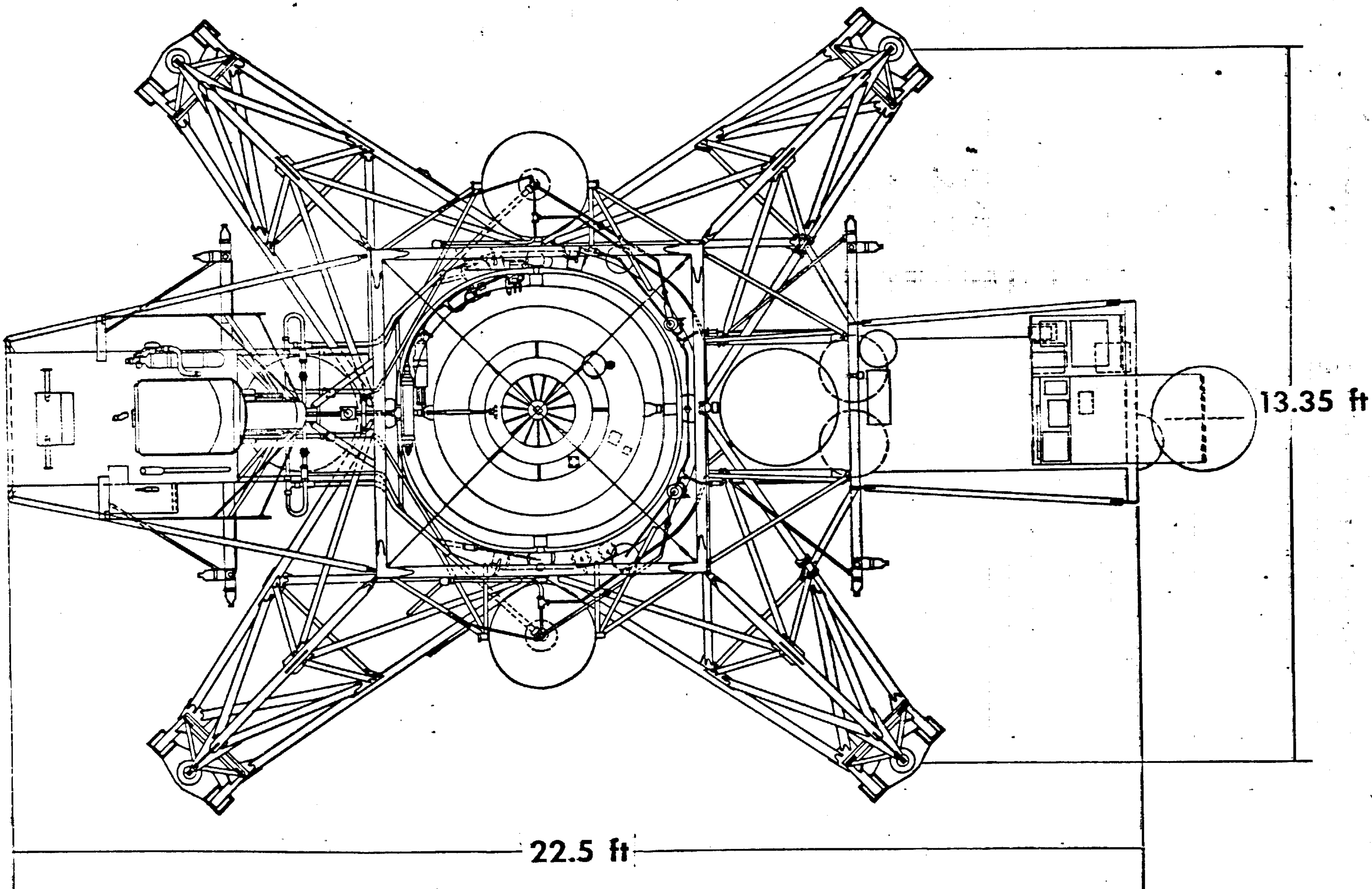
Slide 2

LLRV PROFILE VIEW



Slide 3

LLRV PLAN VIEW



Slide 4

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LLRV WEIGHT TABLE

	WEIGHT, LB
VEHICLE STRUCTURE	665
JET SYSTEM	820
ROCKET SYSTEM	370
CONTROLS AND AVIONICS	205
ELECTRICAL SYSTEM	115
FURNISHINGS	275
RESEARCH INSTRUMENTATION	115
EMPTY WEIGHT	2565
JET FUEL	445
ROCKET FUEL	675
HELIUM, OIL, TRAPPED FUEL	50
PILOT	190
TOTAL USEFUL WEIGHT	1360
GROSS WEIGHT	3925

Slide 5

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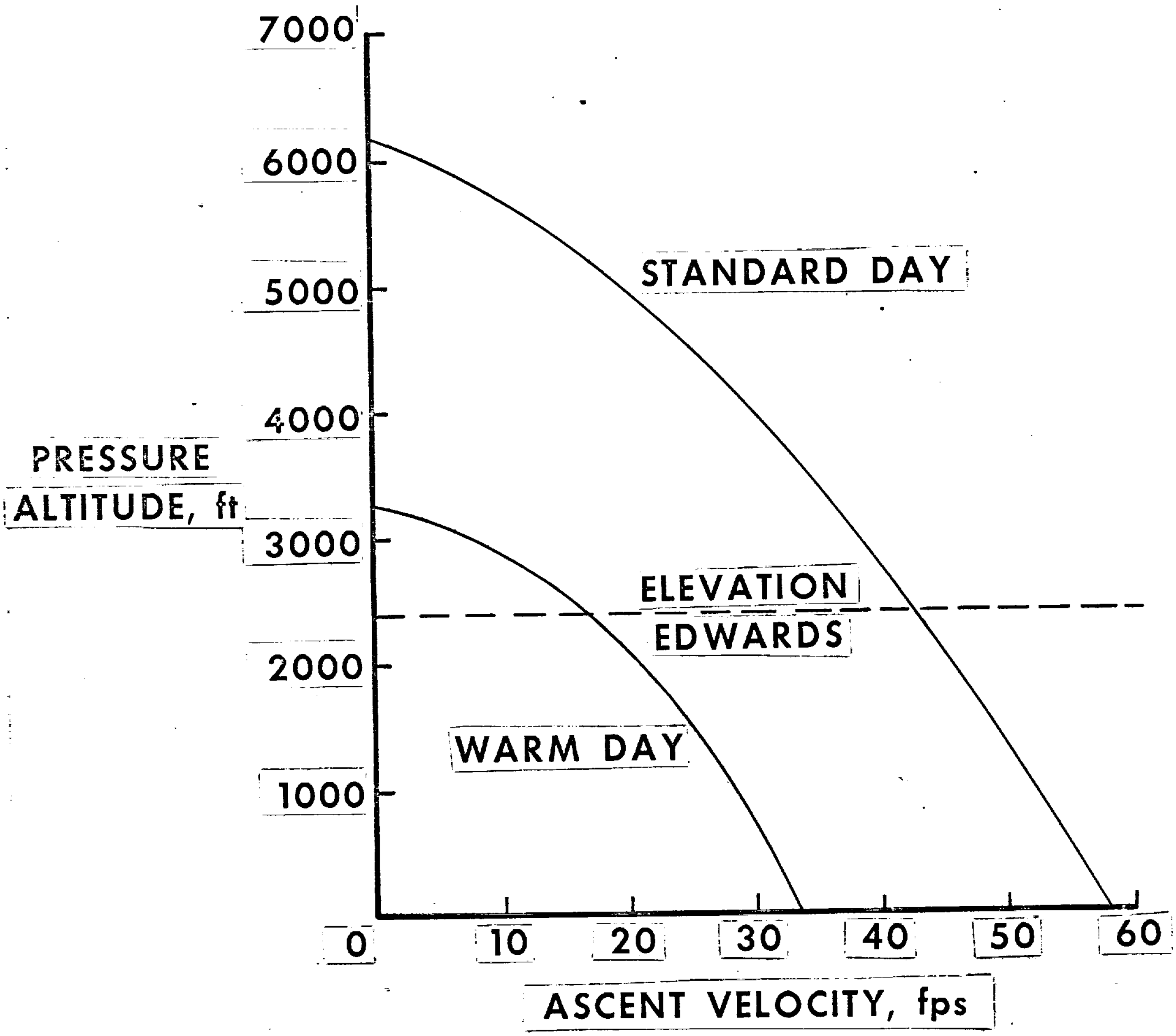
OPERATING ENVELOPE



Slide 6

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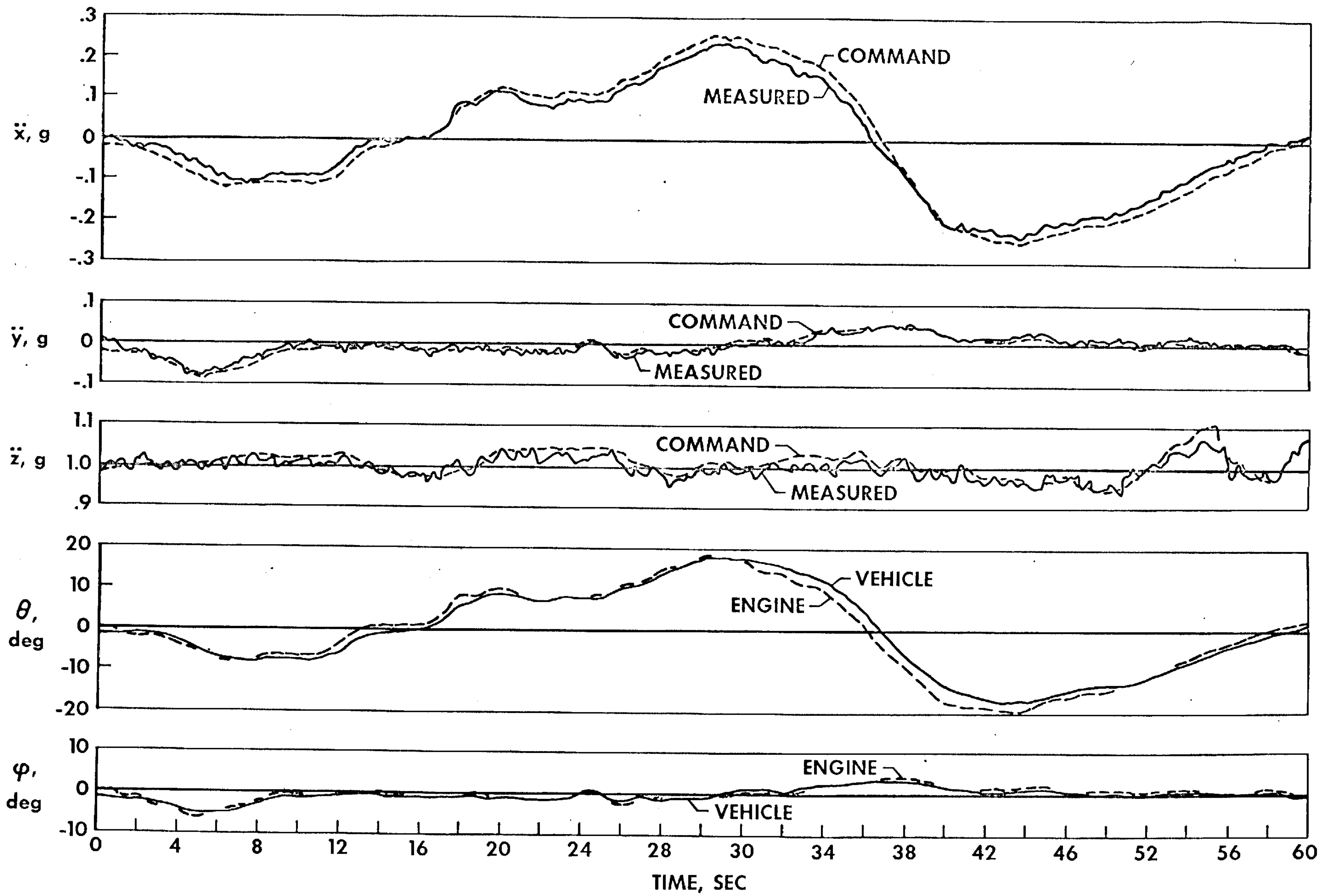
Photo of vehicle tilt.

Slide 7

LLRV LUNAR SIMULATION SYSTEM OPERATION



Slide 8

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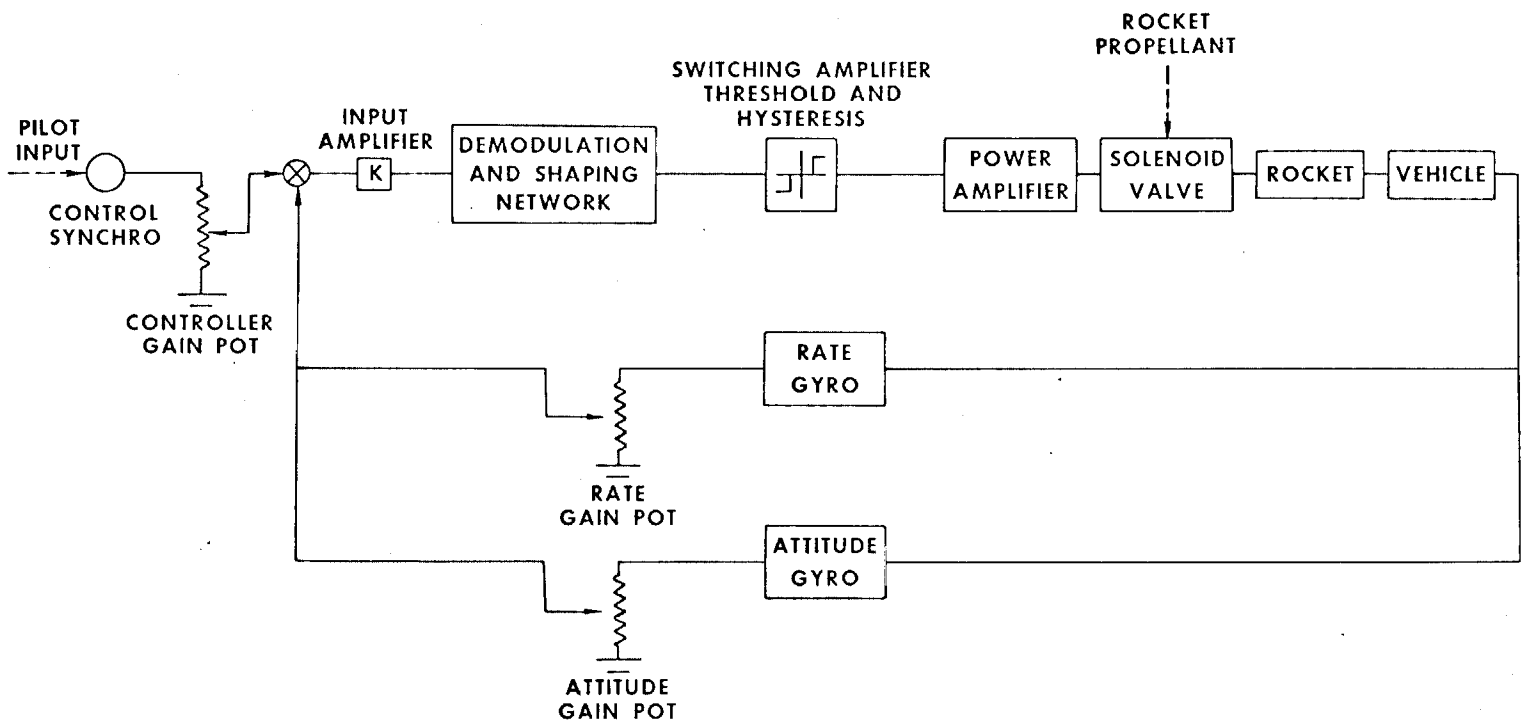
SIMPLIFIED BLOCK DIAGRAM OF LLRV ATTITUDE CONTROL SYSTEM



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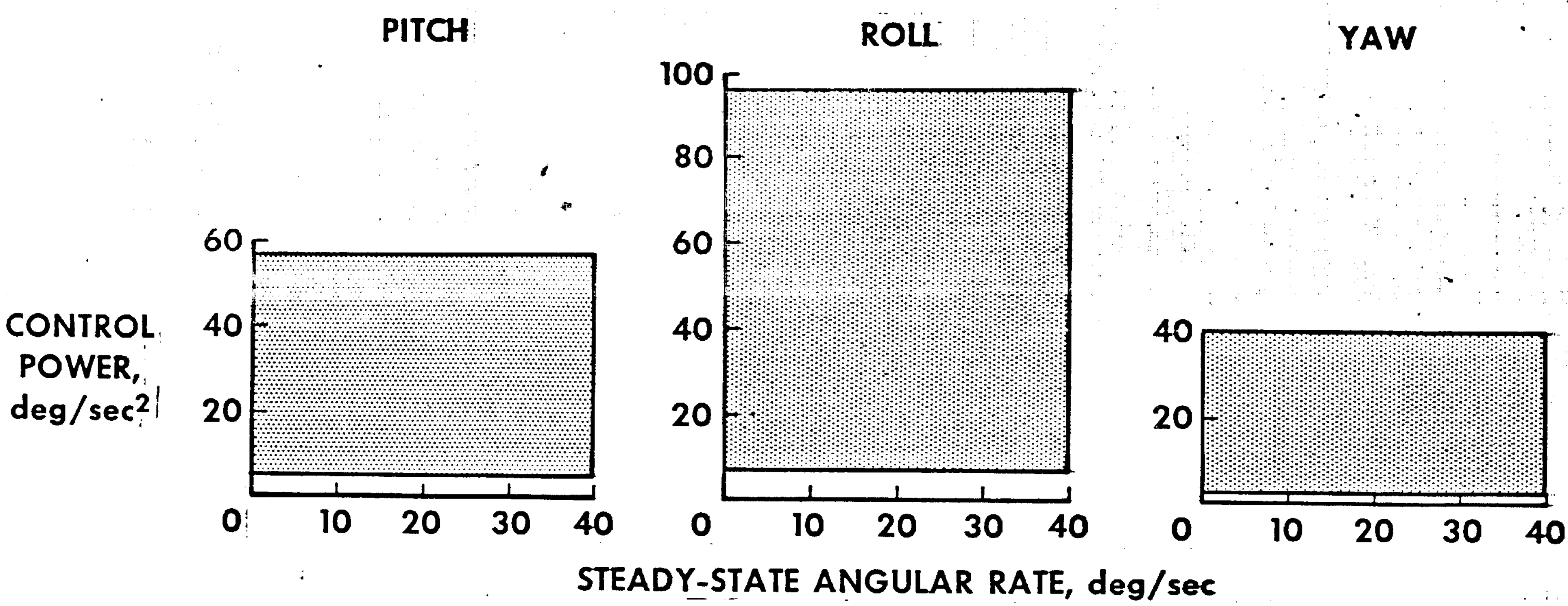
Slide 9

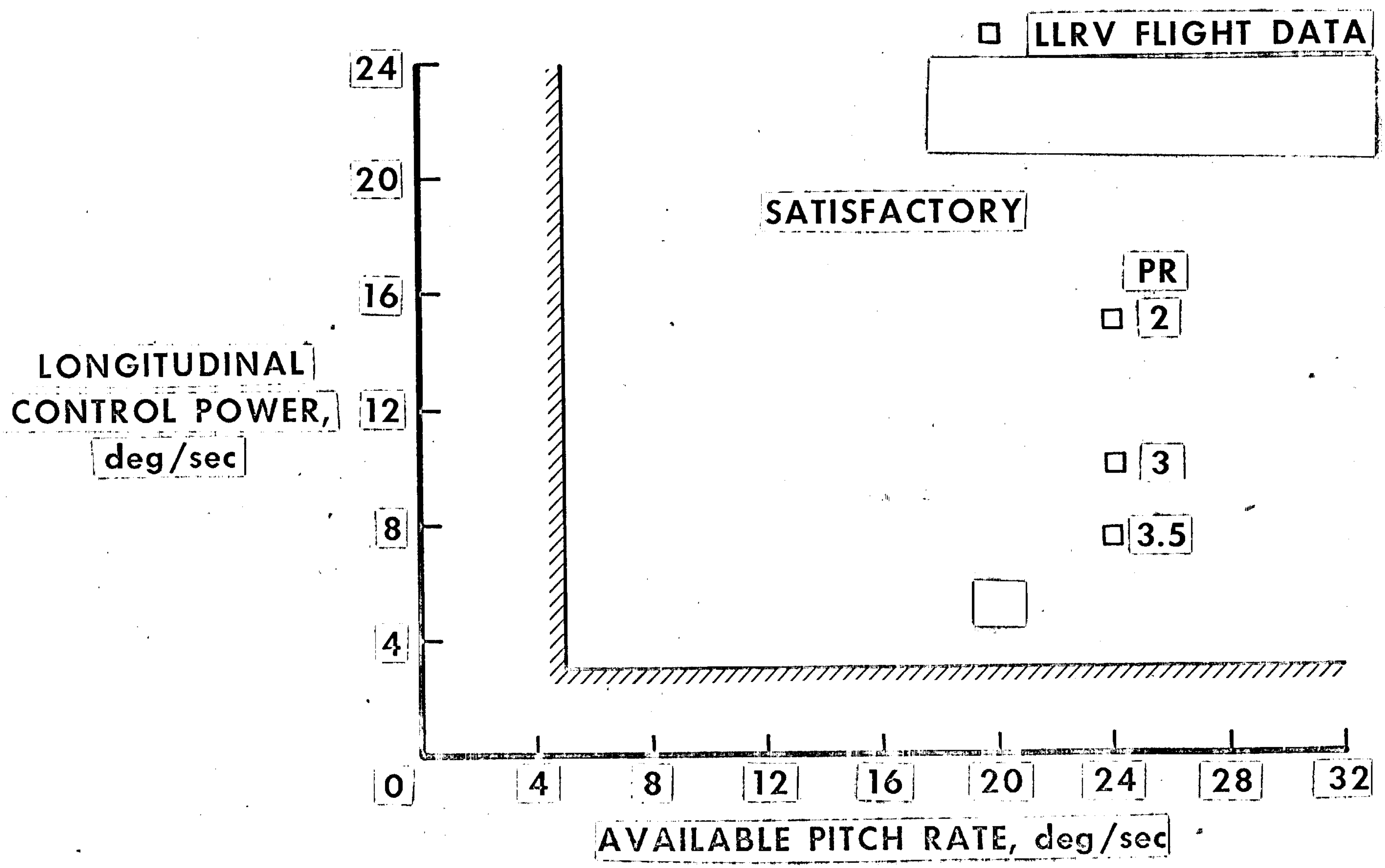
LLRV CONTROL-AUTHORITY VARIABILITY



Slide 10

LLRV HANDLING QUALITIES

RATE COMMAND
2 deg/sec DEADBAND



Slide 11

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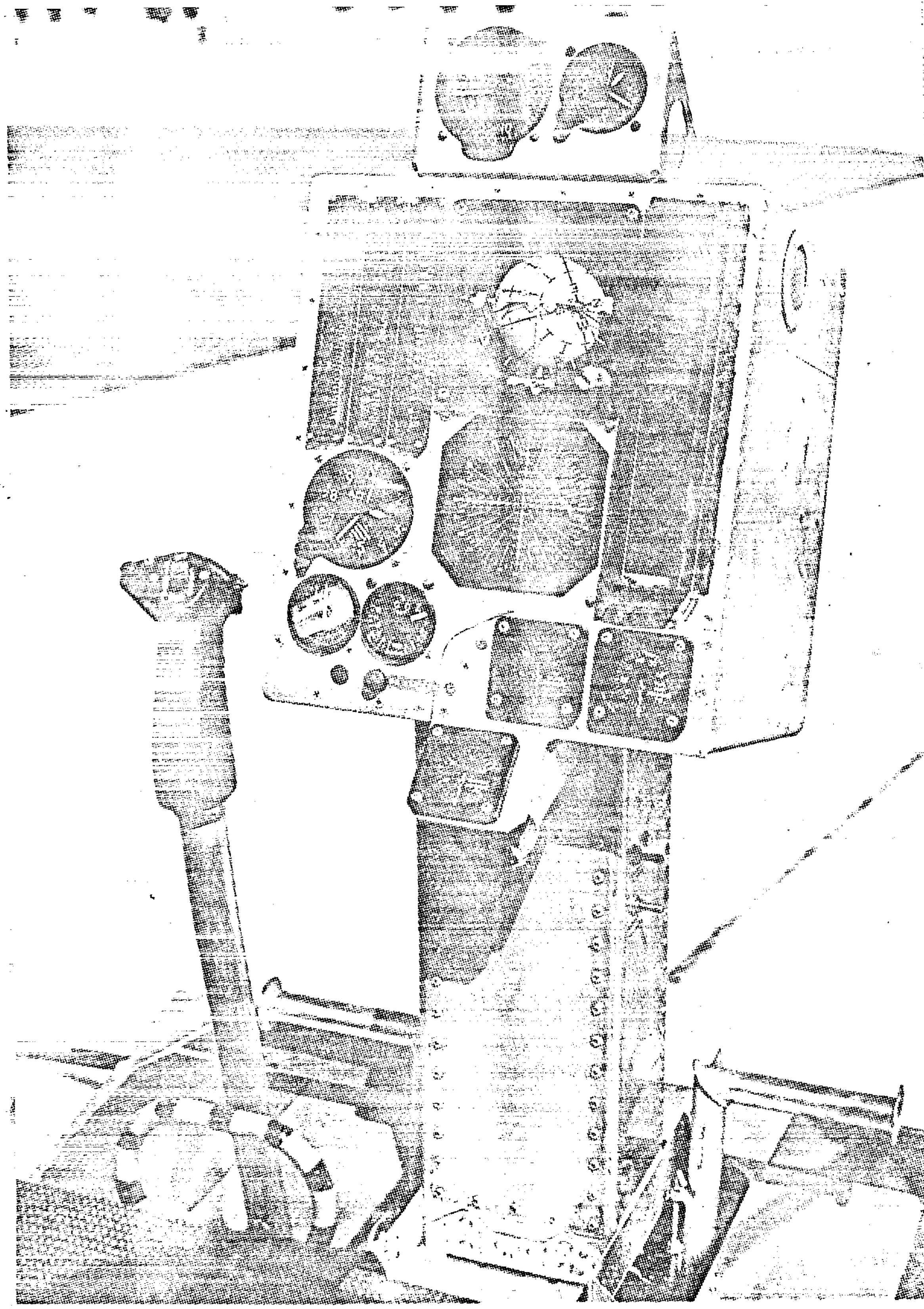
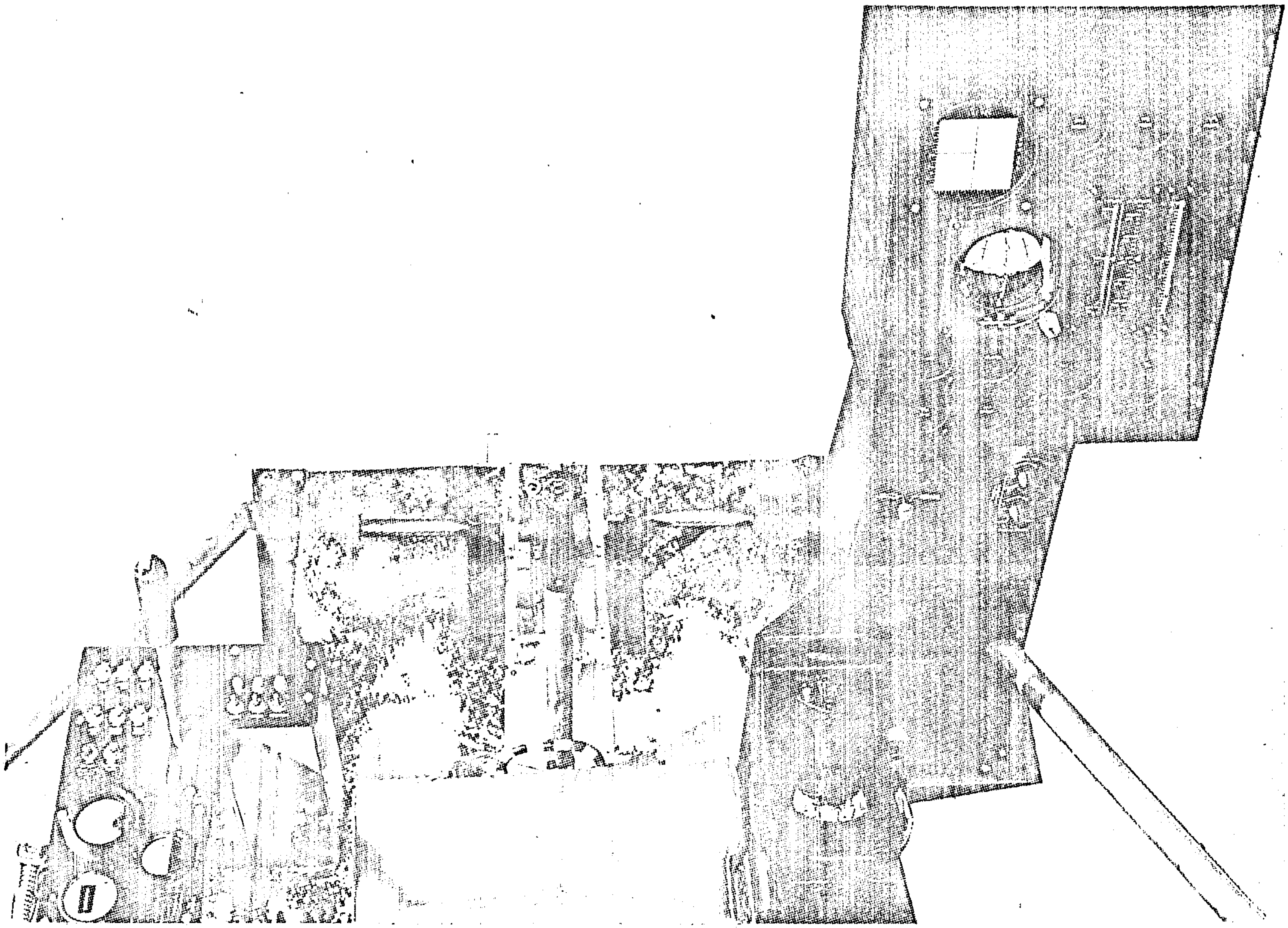
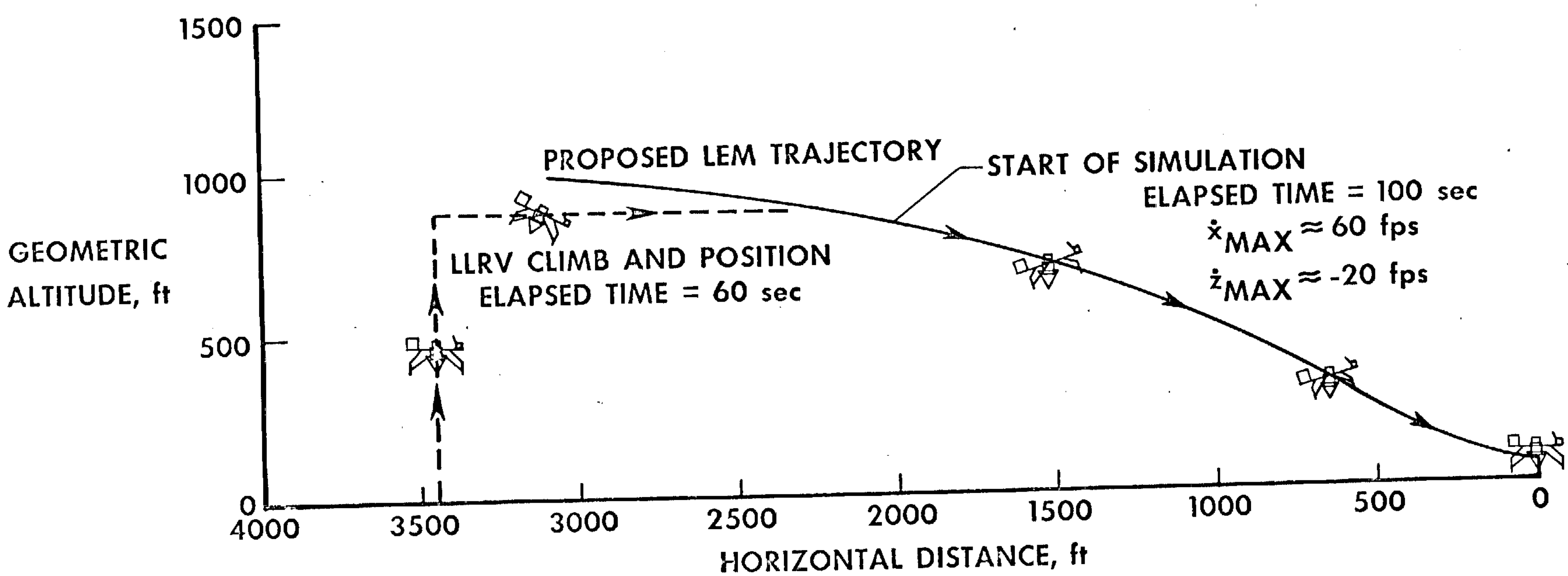


Slide 12



Slide 13

LLRV SIMULATION TRAJECTORY



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Slide 14

LLRV - PILOT IMPRESSION

Our flight experiences with the LLRV have been similar in some respects to those derived from other VTOL programs, and yet I believe, quite different in others. As a general comment, since the majority of our work to date has been involved with adjusting and demonstrating the various systems, these remarks reflect mainly results of flights directed to that work.

On this slide you can obtain an idea of the arrangement of the cockpit. The controls show a strong influence of helicopter cockpit design, and we have had no occasion to regret this approach. Thus the pitch, roll and yaw controls are conventional stick and rudder. The stick moves $\pm$ 8° in pitch and roll, has 1° mechanical deadband, plus approximately 1° more travel to reach electronic threshold. Stick force is about 2# to furnish positive centering. The lift rocket control throttle which is to be used during lunar simulation is the same as a collective pitch stick located here at the left of the seat. Because that location was utilized for the lift rocket stick, the jet engine throttle occupies a conventional location and arc of operation on the left-hand console. The emergency gimbal lock switch and microphone button are located on the control stick grip and all other operations, including selection of attitude control rockets, jet engine mode, etc., are performed by the left hand. Furthermore, this is a wide-open visibility machine, in fact, the transparent panels on the side are retained mostly to protect the pilot some from the attitude rocket exhaust on the forward clusters.

The cockpit arrangement was generated in part prior to any fixed-base ground simulation here at the Flight Research Center, and also amplified and modified as a result of our simulation work which is shown in progress in the first film clip.

I will describe briefly their usage while you observe the operation of the five prime flight instruments. From left to right are the thrust-weight indicator, the vertical velocity indicator, altimeter and attitude indicator. Below the attitude is a ground velocity indicator. The thrust-weight indicator is calibrated in lunar g increments and its response is used for adjusting thrust in hover and to hold constant vertical velocity. The vertical velocity and ground velocity are calibrated in ft/sec. The altimeter reads from zero to 900 ft.

We have found the altitude and vertical velocity readouts, which are derived from a radar altimeter, to be very helpful. For instance, the vertical velocity enables the pilot to establish constant altitude with good precision at heights above the surface which normally require considerable concentration. Recent flights have utilized the doppler ground velocity to good purpose to hold steady longitudinal and lateral translation velocities for control evaluation. As a sidelight, our vertical scale altimeter, because of increased scale sensitivity as altitude is reduced, gives the pilot the same urgent cue to check sinking speed as he obtains from direct vision. The side by side arrangement makes a practical operation of closing the sinking speed to zero at a rate governed by the closure of the altitude to zero.

Indications from the fixed-base simulation were that it would be a difficult vehicle to fly with the gimbal locked unless a rather high amount of attitude control rocket power was utilized. In order to gain some familiarity with the rocket control operation and thrust settings which would seem natural in visual flight, further testing was done on tilt fixtures. During this testing it appeared that we needed to open up the mechanical deadband on the control stick to eliminate sensitivity to unintentional control bursts, although this was not actually done until the first flight where the need was verified. The probable threshold of limit-cycling was checked also on the tilt fixture. We decided that the configuration to be utilized for the initial flight was with the jet engine gimbal unlocked (local vertical), 15°/sec.^{2} maximum control acceleration (pitch and roll), and we would use casters on the main gear in the event of a drift developing. The objective would be to just lift-off the ground, establish a hover, and evaluate controlability; if too much drift occurred, set it back on the ground again.

During preflight checks of control system rockets and lift rockets a fortuitous atmospheric condition caused the following visible illustration of the coupled arrangement of the attitude rockets and the relative amount of thrust between attitude and lift rockets. The first burst was a low thrust normal lift rocket, following by attitude control rockets, and finally all eight normal and emergency lift rockets.

Now observe the first flight operation. There was a small amount of breeze blowing and expected drift did develop, however, it was not a high rate so we were able to get adequate amount of airborne flying time. A little unfamiliarity with jet throttle thrust response brought the not too unexpected results shown here. It wasn't too troublesome as you can observe from the improvement in the second lift-off. The control system locked in both rockets selection so it went into limit cycling at the expense of a lot of fuel, but attitude control was acceptable. Of course, once again, hind sight proved better than foresight, because, after initial operations proved the control system was functional so that we could go ahead with the bimbal locked, we regained control of our own destiny, so to speak, as far as translation was concerned. This later lift-off utilizing jet at slightly less than one g plus normal lift rocket goes quite smoothly.

It quickly became apparent that the greatest discrepancy between fixed-base simulation and flight operation was that what appeared to be a rather difficult task, gimbal-locked, versus an easy one in lunar (gimbal unlocked) condition, was 180° to visual flight experience. However, the fixed-base simulation was quite good as far as establishment of control powers, though a little lacking for good feel of conditions leading to limit cycling of the control system-vehicle loop.

In our next film sequence observe the angular displacement in pitch and roll of the LLRV relative to the jet engine, which remains vertical. We have found this attitude angle, particularly in roll, to be one of the most sensational aspects of flying this machine. One builds up the angle rather cautiously at first, not really believing that it will not go tearing wildly off in the direction of tilt, nor slide down hill toward the ground. The combination of attitude required and time to achieve same leaves an impression of slow motion maneuvering. The technique of control stick movement ranges from short jobs (a sort of dither) at hover to longer duration inputs when maneuvering. These control inputs tend to lengthen as well as increase stick deflection as control power goes down. Control in the yaw axis is possibly the least troublesome of the tasks. Higher rates are built up for large turn angles requiring greater lead for stopping on a desired heading. This landing is being made using the jet gimbal locked configuration but modulating thrust with the lift rockets which is smoother and not as sensitive as the jet throttle. There doesn't seem to be any great difficulty in making a soft touchdown, but close concentration and precision is required for getting the jet centered over a block of concrete, even with the visibility we have.

Here is a re-run of the same kind of flight only with lift-off at higher combined jet and rocket lift thrust, resulting in a rather spectacular ascent. The LLRV appears to be very "busy" with all the bursts of steam from the lift and control rockets. You are observing the visual evidence of the audible sensations which prompted one observer to describe it as a "battle going on all by itself".

We are able to hear the control system pulses during flight and to some extent determine the quality of operations. Some impression of speed is derived here from the relative drift of the steam bursts. At touchdown you can see an indication of the rebound problem if thrust is not chopped promptly.

Generally a control power resulting in 15° sec ^{2} acceleration maximum has been good for operation in both the gimbal lock and lunar simulation configuration, although it is apparent that the reduction of inertia and lower thrust for manuevering with jet gimbal unlocked makes lower control powers acceptable or even desirable in order to avoid over-controlling. On the other hand, as the control thrust goes down, finally maximum attitude rate attainable becomes reduced to the point where the pilot senses that he should not allow the vehicle to get into a combination of attitude and ground proximity or translation change requirement which requires correction in a short period of time. He prefers not to use full authority for normal control, reserving a cushion for a safety factor. Also the pilots expressed the desire for greater yaw control power, when faced with requirements for large yaw angle changes, in order to reduce the time consumed. Thus we are faced with an operational compromise between a natural desire fuelwise to reduce the control thrust and still retain adequate maneuvering response. A better answer to this situation would be the ability to either use translational thrust rockets or change the main lift rocket thrust vector angle while maintaining the vehicle attitude level.

Though we have intended using only rate command attitude control, on some occasions the yaw system has switched into the backup mode, which in that axis results in acceleration command. About the only thing was observed of any great significance was that the pilot tended to let drift rates increase to higher values than the normal rate deadband before accomplishing the correction. Hence, longer periods between control damping inputs and longer duration pulses. He tightened up the loop during landing, however. The only problem we have had during take-off has been the surface temperature bringing our available thrust down near that required by the weight of the vehicle resulting in slow ascent necessity to sit and burn off fuel. Deletion of casters in favor of pads has not caused any trouble. Pre-take-off drift has been reduced.

There has been no confusion of any consequence involved with controlling altitude and altitude rate by fore and aft movement of the normal jet enging throttle vs. up and down collective operation of the lift rocket stick. The function appears normal in sense for both, and has not caused problems while switching back and forth even close to the ground during landing.

The attitude control rockets furnish adequate acceleration input, so when the pilot operates the controls to cause a movement of the vehicle he immediately gets response. It results in jerky response at high control power which smoothes out as control power decreases. On one flight I achieved a high enough forward velocity with a control rocket setting of $8°/sec^2$ that a limitation on control was apparent in a forward descending condition. I was obviously running out of control to hold the nose down and it was necessary to decrease speed in order to retain sufficient control margin.

This leads us into consideration of the fidelity of simulation of lunar operation utilizing this machine. I am convinced that under hover conditions and low translational speed any control requirements, decisions and experiences which we achieve are completely reliable and would represent an accurate prediction for those necessary on the actual lunar excursion module. That brief amount of experience which we have at higher speeds leads to the conclusion that we can only talk conservatively about control requirements at relatively high translational velocities, because, although we have drag compensation built in, we still have the unbalance moments on the vehicle which need to be compensated and hence use some of the control power. Thus a control configuration which appears to have a good rating in hover and at very low speeds becomes marginal as we pick up higher speeds. I feel that with the auto throttle mode and the jet stabilization system functioning, the pilot operating the lunar landing research vehicle is getting a accurate picture of what he will experience operating the lunar excursion module. The vehicle angular displacements required for sensible translation adjustments are supplied, and render a clear message of caution to the pilot relative to translation near touchdown. Granted that at this point we have been operating completely visual.

One aspect of fidelity of simulation which should not be overlooked is the fact that our rocket propellant supply is of limited duration so that the sense of limited amount of time for approaching the surface and landing under control is rather well duplicated. As inferred earlier, the effect of change of moments of inertia of the same order of magnitude as that of LEM shifting from descent to ascent configuration is being demonstrated.

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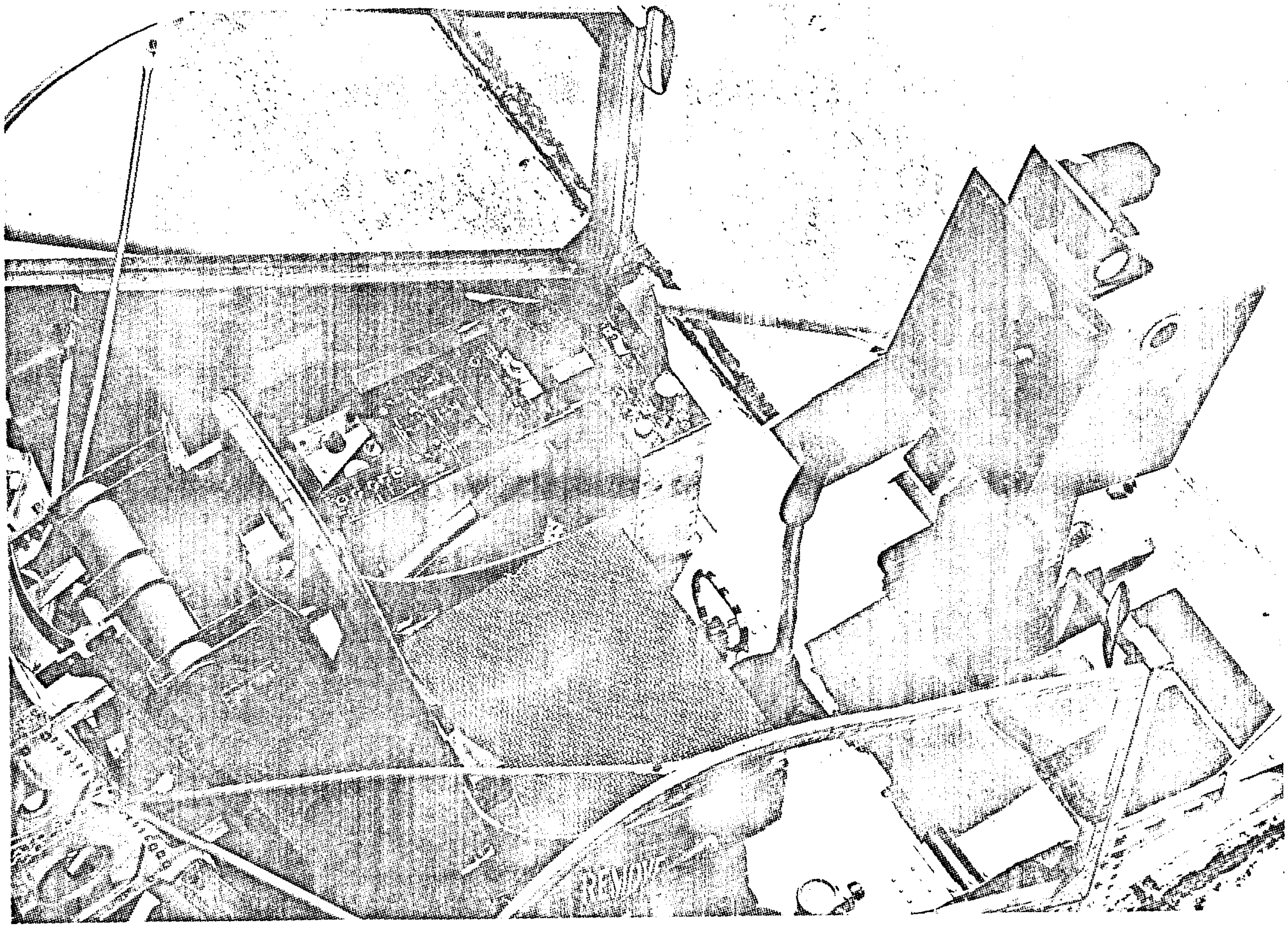

Slide 1