N84 10170

FLYING THE ORBITER IN THE APPROACH/LANDING PHASE

Steven R. Nagel
Johnson Space Center
Houston, Texas

INTRODUCTION

The Columbia has completed a spectacularly successful four flight Orbital Flight Test program as well as the first operational mission in which two satellites were deployed. As we await the first launch of the next Orbiter, Challenger, it is an appropriate time to reflect upon some of the accomplishments of these five flights as well as areas of desired improvements. John Young's description of the Orbiter as a "fantastic flying machine" is an accurate representation of the opinions of all the crew members who have flown on the Columbia to date. It is unprecedented that a vehicle so complex as the Shuttle could have reached such a state of maturity in so few missions. This maturity is reflected not only in terms of basic performance during dynamic flight phases, but also in the outstanding performance of individual spacecraft systems. Certainly, one purpose of this paper is to extend to you, the designers and developers, the heartfelt thanks of the crew members who are very pleased to have the opportunity to fly your Space Shuttle. When attempting to describe how the Shuttle flies, one should look at the phase where most of the "hands on" activity has occurred. Appreciably more CSS time has been logged during entry and particularly in the approach and landing phase than any other segment of the mission profile. The discussion that follows, therefore, will outline this phase in some detail including pilot comments, techniques, crew displays and landing aids. Some problem areas related to landing the Orbiter will be discussed, as well as possible solutions.

ABBREVIATIONS AND SYMBOLS

A/L	Approach and Landing
CG	Center of Gravity
CRT	Cathode Ray Tube
CSS	Control Stick Steering
FCS	Flight Control System
HAC	Heading Alignment Circle
HSD	Horizontal Situation Display
HUD	Heads Up Display
IGS	Inner Glide Slope
KEAS	Knots Equivalent Air Speed
OGS	Outer Glide Slope
PAPI	Precision Approach Path Indicator
RHC	Rotational Hand Controller
SES	Shuttle Engineering Simulator
STA	Shuttle Training Aircraft
STS	Space Transportation System
TAEM	Terminal Area Energy Management
γ	Flight Path Angle
$C_{L_{\delta e}}$	Change in lift coefficient with elevator deflection
$C_{L_{\alpha}}$	Change in lift coefficient with angle of attack

SETTING UP THE APPROACH

The entry is a progression of events designed to place the Orbiter in a position from which a safe landing can be made. It does this without violating thermal, dynamic pressure, or acceleration constraints for those trajectories within a given dispersion band. Guidance modes for the overall entry fall into three phases:

- o Entry Guidance
- o TAEM Guidance
- o Approach/Landing Guidance

The purpose of Entry Guidance is to deliver the Orbiter to the TAEM interface conditions which are relative velocity of 2500 ft/sec, altitude of approximately 82,000 ft, range of approximately 52 NM, and heading within a few degrees of that required to fly to the tangency point of the appropriate HAC.

TAEM guidance is divided into four subphases as depicted in figure 1. At the end of TAEM the Orbiter is established on the outer glide slope (OGS), on runway centerline and on airspeed.

Approach and Landing (A/L) guidance begins with termination of the TAEM phase and ends when the Orbiter completes rollout. The phases of A/L guidance are depicted in figure 2.

FLYING THE APPROACH

To a large extent the landing point and even quality of touchdown depend upon flight conditions at the preflare point where the Orbiter is transitioned from the OGS to the inner glide slope (IGS). If airspeed, flight path angle, and position are very close to nominal, the end result will likely be a satisfactory touchdown at the desired point. On the other hand, if dispersions of appreciable magnitude exist at preflare, the landing may be salvaged but will probably not occur at the desired point. To assist the crew member in achieving the planned trajectory, several displays and landing aids are available both inside the cockpit and on the ground.

In the cockpit are three types of displays: dedicated, CRT, and the HUD. Dedicated displays are those meters that give classic flight parameters such as airspeed, altitude, angle-of-attack, etc., as well as the attitude and heading indicators. Steering needles on the attitude indicator reflect guidance commands to remain on or correct to the proper trajectory. See figure 3.

The only CRT display that might be used during the approach and landing phase is the Horizontal Situation Display (figure 4). The HSD presents a horizontal depiction of the Orbiter's flight path relative to the HAC and final approach. Its real usefulness is for flying around the HAC, but the HSD may also be used on the OGS, especially if weather is present.

The HUD will be flown for the first time in Challenger and represents a significant improvement to the task of flying or monitoring the final approach and landing (figure 5). All flight critical information is presented on the HUD combining glass so the crew member does not have to go "heads down" during the approach. Additionally, the HUD has a velocity vector which depicts the real time flight path of the Orbiter, thus making the results of any correction to glide path or azimuth immediately apparent. Declutter modes allow certain symbology to be removed from the HUD when not required.

Using these onboard displays the crew member can fly the entire approach by satisfying guidance commands (i.e. centering the needles). Prudence dictates that one also crosscheck the "raw" data - flight conditions and position relative to glide path and runway centerline. And of course, even though we completely trust the onboard indications, it never hurts to take a look out the window.

To assist in the problem of visually acquiring the OGS and IGS, three aids have been placed on the ground: aim point markings, PAPI's, and the Ball-Bar. Markings have been placed at the ground intersection points for the OGS (figure 6). The standard OGS aim point is a rectangle located 7500 ft from the runway threshold while the high wind OGS aim point is a triangle placed 1000 ft closer. When on the OGS the Orbiter is on a collision course with the appropriate aim point until preflare. As a matter of fact, the velocity vector in the HUD (-o-) should overlay this aim point while on the OGS.

Of course, just aiming at the proper point on the ground does not assure the correct flight path angle (normally 19°). To provide a visual aid for gamma (γ) Precision Approach Path Indicator (PAPI) lights are installed at the aim points (figure 7). Each light has a split beam the upper half of which is white and the lower half red. The four lights are set at 22°, 20°, 18°, and 16° elevation respectively. Thus, when one flies down a 19° γ glide path he will see two white lights and two red lights. Likewise, three red and one white light indicate that at that moment the Orbiter is on a 17° γ glide path, and so on.

After many attempts at visual aids for flying the 1 1/2° γ IGS, the Ball-Bar was developed (figure 8 .) The Ball-Bar is so straight forward and simple one would wonder how it belongs in the Space Program. Placed beside the runway and 2200 ft from the threshold, the Bar is an array of six groups of red lights, all set two feet above the ground. In front of the Bar 500 ft is the Ball, a cluster of three white lights on a pole 15 ft tall. A line drawn from the Bar through the Ball subtends an angle of 1.5° from the horizontal. Thus, when the pilot flies the Orbiter to line up the Ball and Bar, he is on the proper IGS - and it works extremely well.

PILOT COMMENTS AND PROBLEM AREAS

The first five Shuttle missions have had varying amounts of manual flying on the HAC and final approach. All landings thus far have been manual. During STS-1 and 5 the commanders were in CSS from approximately 35,000 ft all the way to touchdown. On STS-2, 3, and 4 there were varying mixtures of AUTO and CSS through this phase depending upon the test objectives for each particular mission.

In general, the pilot assessments of the Orbiter subsonic handling qualities are quite favorable. "Smooth, crisp, and precise" are terms that have been used to describe the FCS. Although it is a rate command system, the rate deadbands are so tight that the FCS behaves almost as an attitude hold system. Most pilots have stated that the Orbiter is tighter and more responsive than the Shuttle Training Aircraft (STA/Gulfstream II). The only slight exception to this statement might be with regard to the speedbrake which has rather slow response and poor anticipation for speed control when in AUTO. Many pilots use the technique of manually setting the speedbrake until close to the desired airspeed, then allowing AUTO to assume vernier control.

Along with all the good things that may be said about the Orbiter, there are a couple of areas in which problems may arise sooner or later. Those two areas are the last key events of any mission - landing and stopping.

The Orbiter is not a straightforward and easy airplane to land for at least two reasons. Conventional aircraft exhibit positive speed stability such that for landing the pilot is continually applying increasing aft stick to "hold the airplane off" during the final flare. The Orbiter, with its very tight rate command system, will essentially hold attitude with the RHC in detent. Thus, in landing the Orbiter, one makes short, pulse inputs for fine corrections in the flare, as opposed to increasing back pressure. Additionally, the Orbiter is a large delta wing airplane with an unusually high ratio of elevon area to total wing area (the elevons comprise more than 15% of the total wing area). The well known result is that a pitch command in one direction results in an initial translation in the opposite direction due to the $C_{L_{\delta e}}$ effect until the aircraft rotates enough for C_{L_α} to produce the desired response (figure 9.) The bottom line is that any large RHC deflections just above the runway are taboo. All this works very well for a good setup with no gust upsets or other unforseen occurrences. Given off nominal conditions, however, the pilot may have to increase the magnitude of RHC inputs and the result may well be a hard landing. After main gear touchdown the nose gear is lowered to the runway, nominally at 180 KEAS. On STS-3 during the derotation, a pitch instability was discovered. Subsequent analysis confirmed the existence of this instability with weight on main wheels, low pitch attitudes, and forward C. G.'s. Several candidate modifications to the CSS pitch axis for slapdown/rollout were examined in the Shuttle Engineering Simulator (SES). One of the simplest proposals turned out to be the most satisfactory; switching the CSS flight control configuration to the AUTO loop gains at weight on main gear resulted in a very tight, well damped pitch axis.

Once on the runway and derotated, the final objective is to bring the Orbiter safely to a stop. Original design requirements called for touchdown speeds in the neighborhood of 150 KEAS. With several years of weight growth in the design, however, landing speeds have increased drastically. For example, the reference touchdown speed for STS-6 end of mission is 185 KEAS and abort touchdown speed is 205 KEAS. Although they have been improved, the brakes and tires are marginal for heavyweight aborts into short runways.

POSSIBLE SOLUTIONS

Considering first the stopping problem, there are several candidate solutions, some of which are more reasonable than others.

1. Lengthen the short runways
2. Install a drag chute in the Orbiter
3. Install runway barriers
4. Improve brakes, tires, axles
5. Optimize pilot braking technique
6. Develop a closed loop speedbrake logic to reduce landing dispersions

The last three options on this list show some promise and number 6 in particular is interesting. Presently the speedbrake closes at 4000 ft, 2500 ft, or 1000 ft altitude, depending upon energy, and remains closed until touchdown. The "smart" speedbrake logic proposes to control velocity versus x distance from the runway to cross the runway threshold at a given delta above reference touchdown speed. For a nominal landing this delta would be +25 KEAS whereas for an abort it would be +5 KEAS. The result, for example at Dakar, would be a touchdown 2000 ft down the runway at 15 KEAS below nominal touchdown speed.

Orbiter landing handling qualities remain a concern. Several proposed modifications to the CSS pitch axis for landing are presently undergoing evaluation in various engineering simulators. It remains to be seen if any one of these candidate FCS changes is sufficiently better than the baseline system to warrant incorporation. As stated before, to a great extent, the problems close to the runway are related to the physical configuration of a delta wing with large elevons. One way to alleviate this problem is to incorporate active canards. Canards could produce benefits to the Orbiter in many different areas, a few of which are:

1. Active canards for pitch control could eliminate the adverse $C_{L\delta e}$ effect and thus solve the landing longitudinal control problem.

2. With active canards the elevons could be deflected down during landing to serve also as flaps. The decreased touchdown speeds would solve the stopping problem and save the expense of frequent brake refurbishment.

3. Canards would increase L/D, thereby permitting a shallower steep glideslope and decreased pilot workload.

4. By reducing landing speeds and controlling pitchover, canards could reduce the large negative lift loads on the gear and tires resulting from up elevons at nose gear touchdown.

5. After derotation the negative angle of attack provides desirable aerodynamic braking but also imposes large loads on the gear and tires. With reduced landing speeds provided by canards, the nose gear could be extended to alleviate this gear load problem.

CONCLUSION

The Shuttle has continued to impress all of us with its capabilities and performance throughout the envelope. It enters the operational phase backed by many years of development and testing as well as a successful four flight test program. Future flights will see implementation of new elements and design features as the program moves towards even better performance. Along with these changes will come unforeseen problems that will be solved as have those in the past. But one thing is certain - the Shuttle concept is a sound one and will allow us to attain a routine presence in space.

BIBLIOGRAPHY

"GNC ENT 2102 GN and C Entry Operations Guidance and Navigation," Advanced Training Series, NASA Johnson Space Center, April 1982.

Mattingly, Thomas K.; and Hartsfield, Henry W., Jr.: Space Shuttle Progress Report. The Society of Experimental Test Pilots 1982 Report to the Aerospace Profession 26th Symposium Proceedings. September 1982, pp. 267-285.

Stegall, H.: "Altitude Rate Response of Shuttle During Landing Approach and Proposed Handling Quality Candidate," NASA TM EH 23A08-04, Jan. 20, 1983.

ORIGINAL PAGE IS OF POOR QUALITY

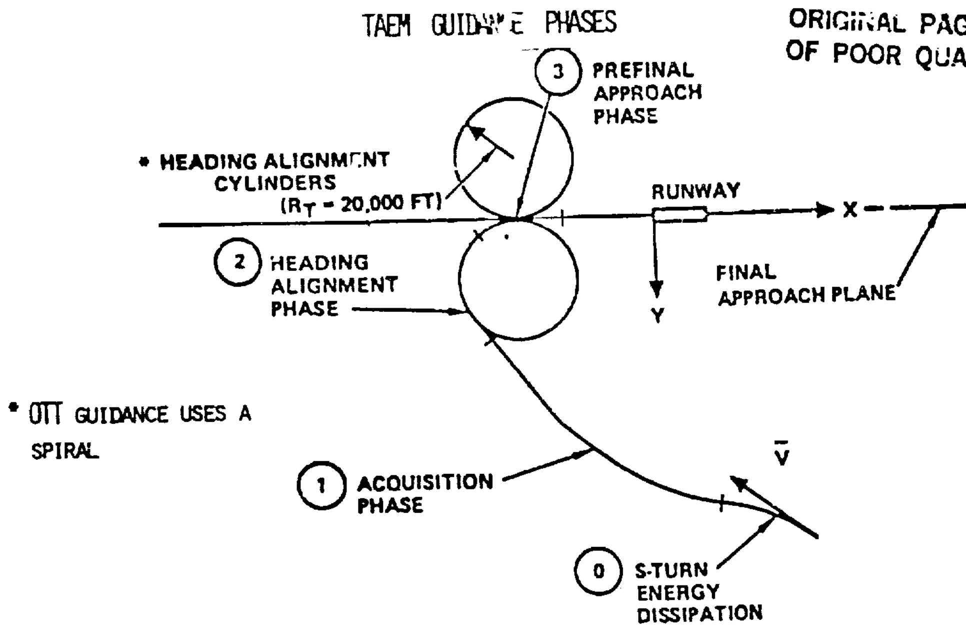


Figure 1

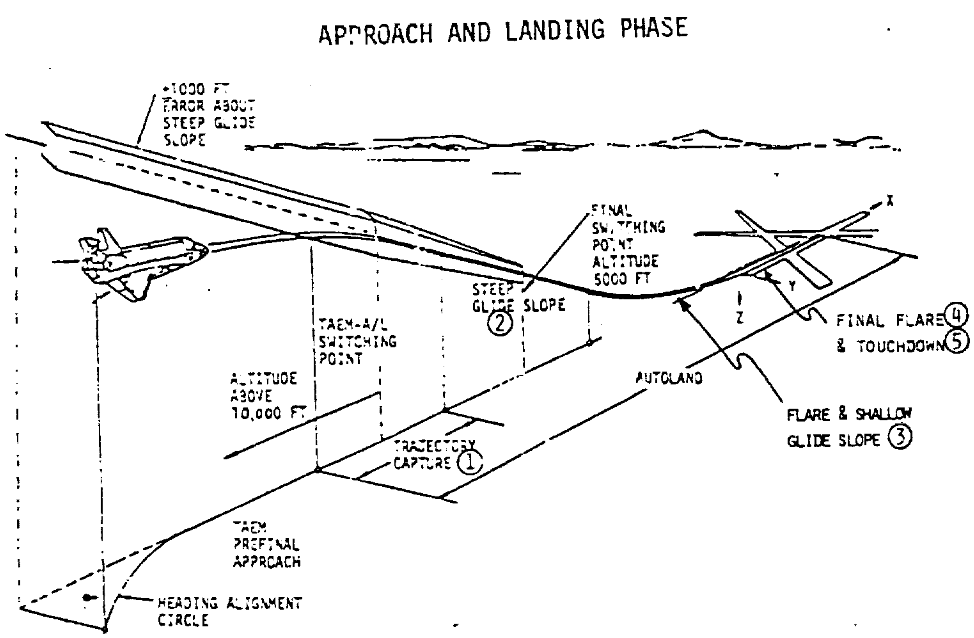


Figure 2

ORIGINAL PAGE IS
OF POOR QUALITY

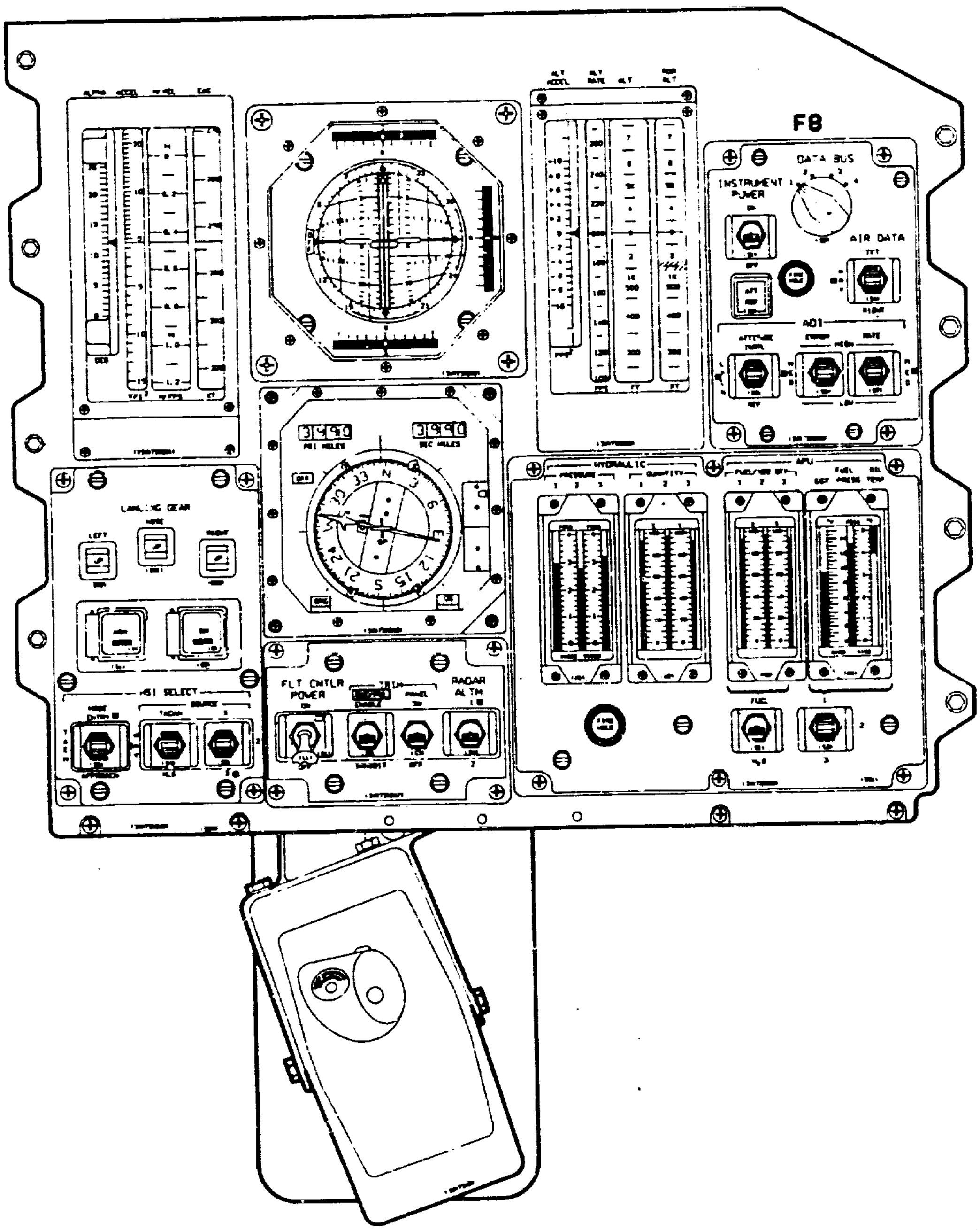


Figure 3

HORIZONTAL SITUATION DISPLAY

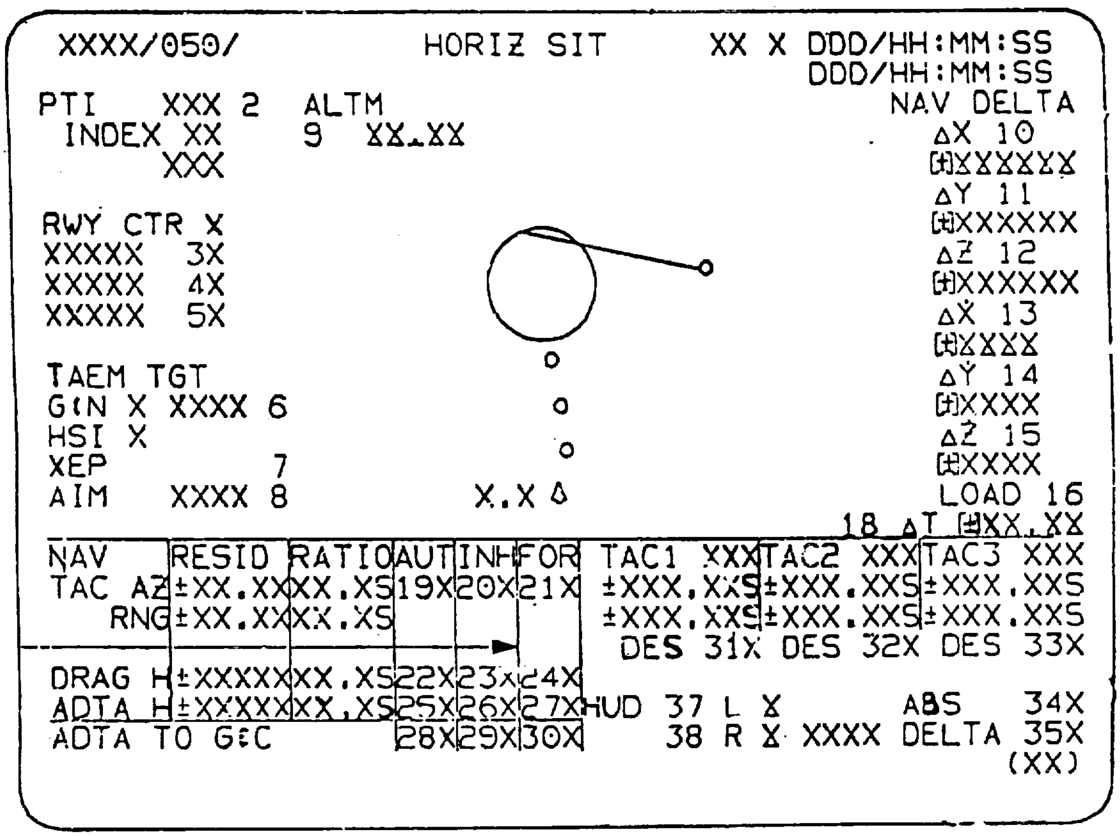
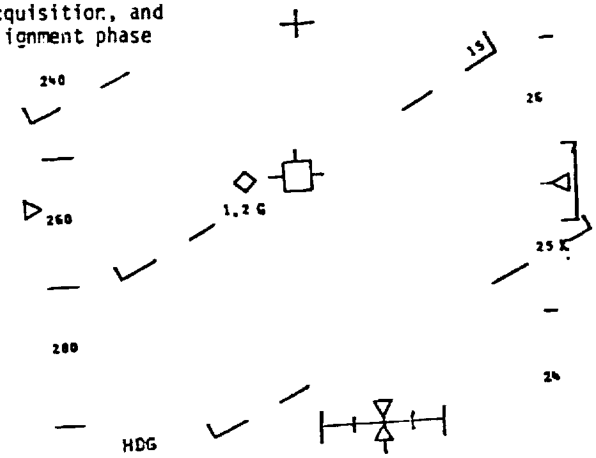


Figure 4

HUD FORMAT

S-turn, acquisition, and heading alignment phase



The approach and land HUD format

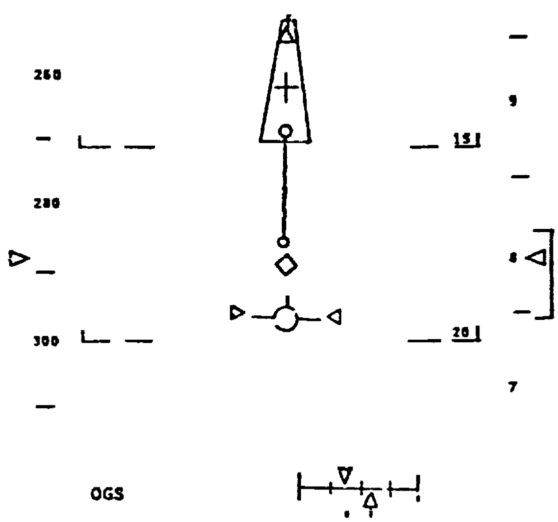


Figure 5

ORIGINAL PAGE IS
OF POOR QUALITY

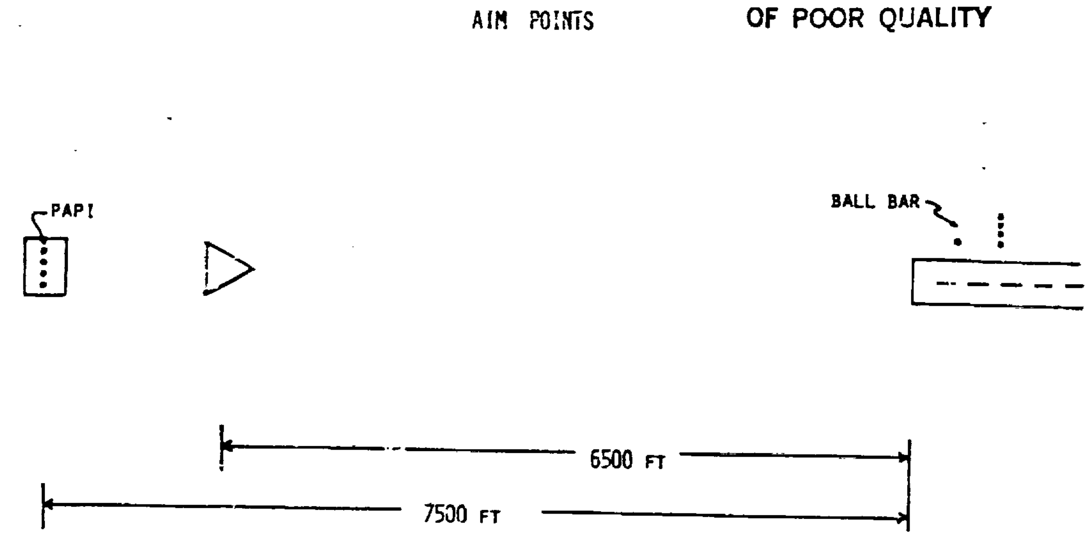


Figure 6

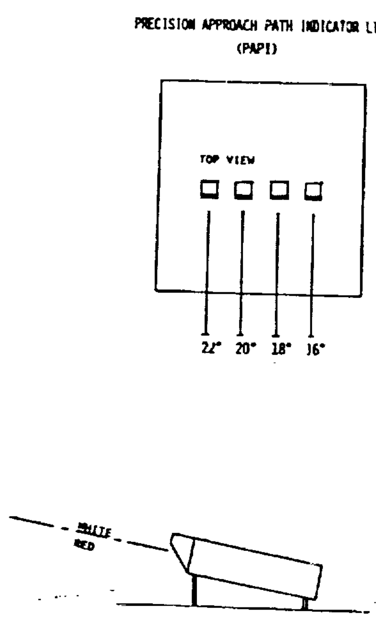


Figure 7

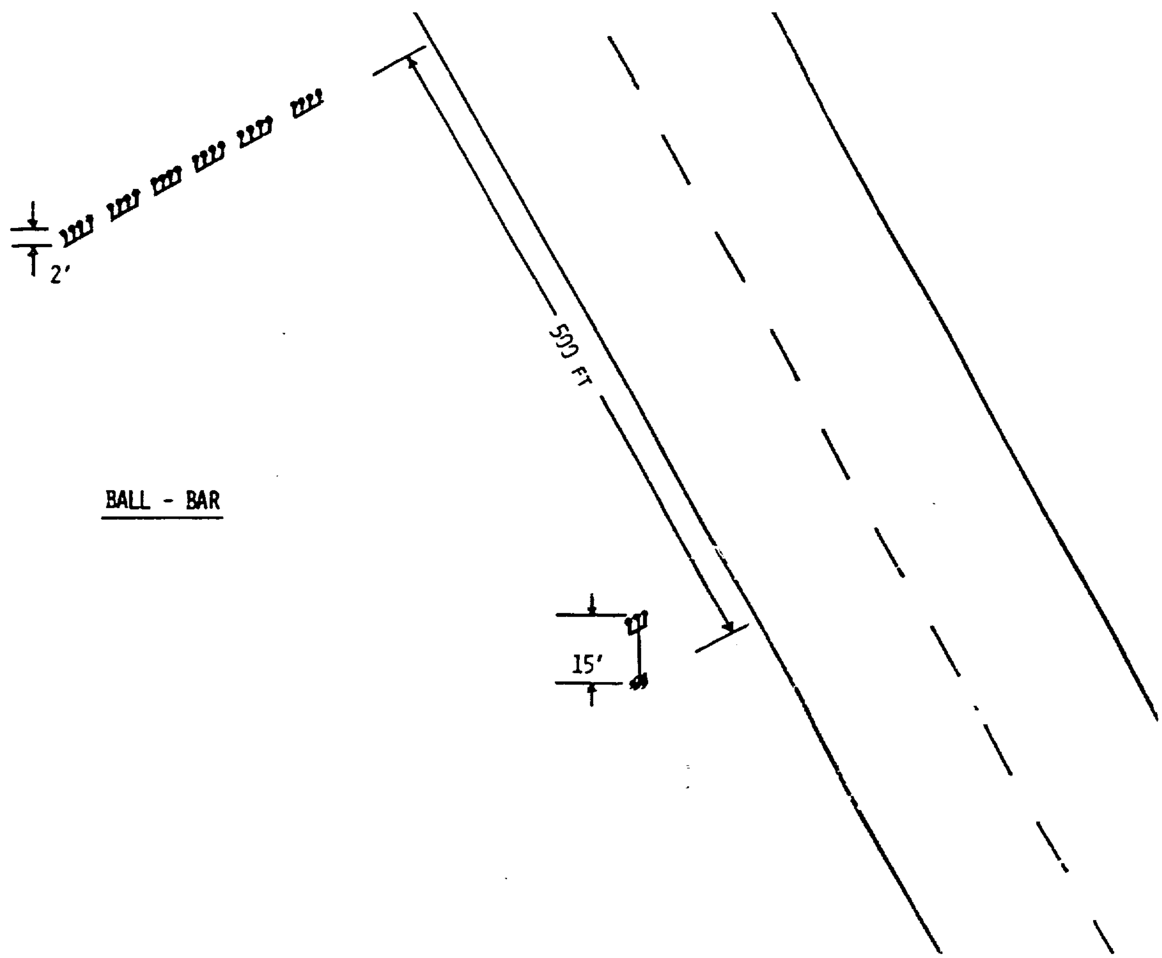


Figure 8

ORIGINAL PAGE IS
OF POOR QUALITY

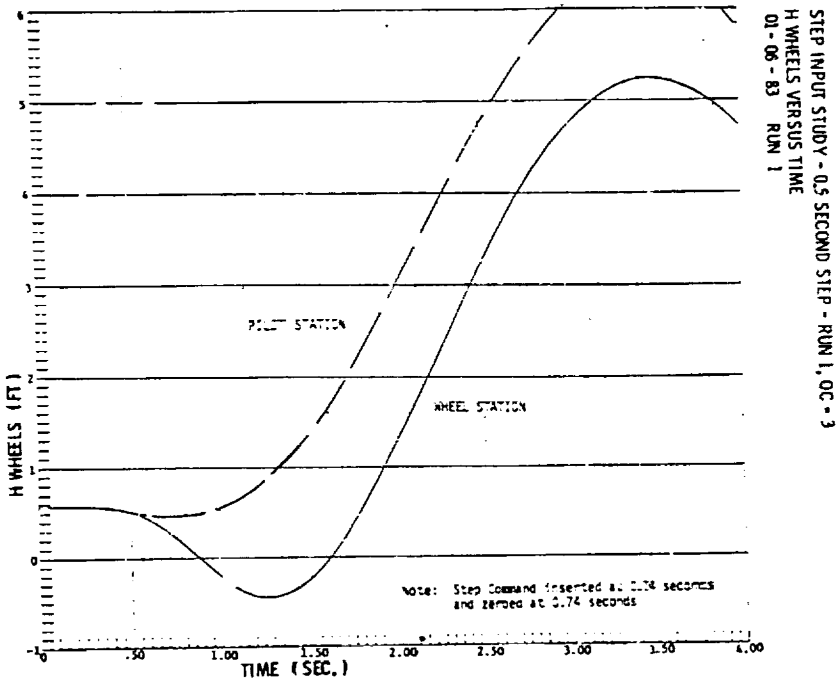


Figure 9

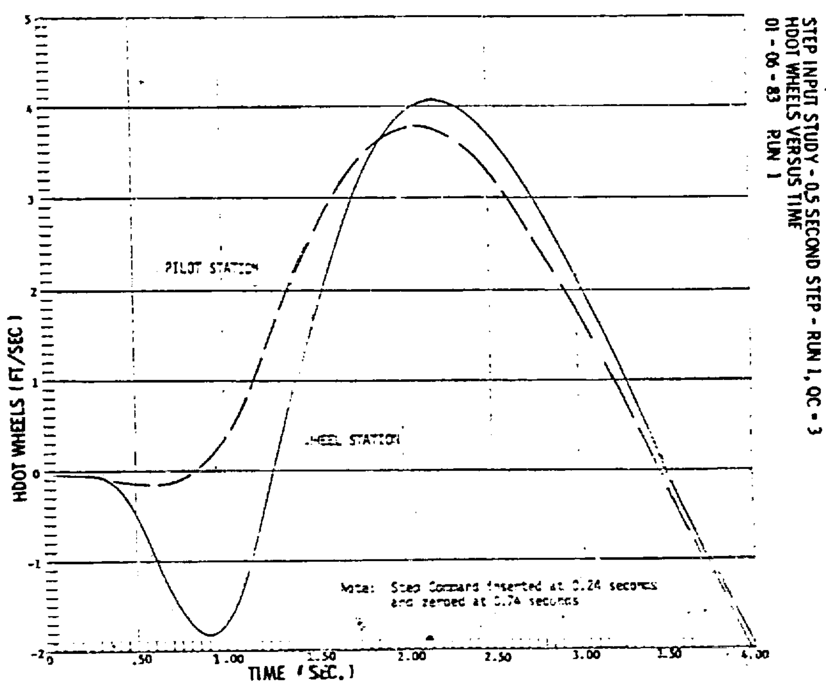


Figure 10