Go For Lunar Landing Conference: From Terminal Descent to Touchdown March 4th and 5th, 2008 Tempe, AZ

Panel #1, Apollo Team: Lunar Landing Research and Training Vehicles (LLRV & LLTV)

Go For Lunar Landing Conference, March 4 -5, 2008, Tempe, AZ

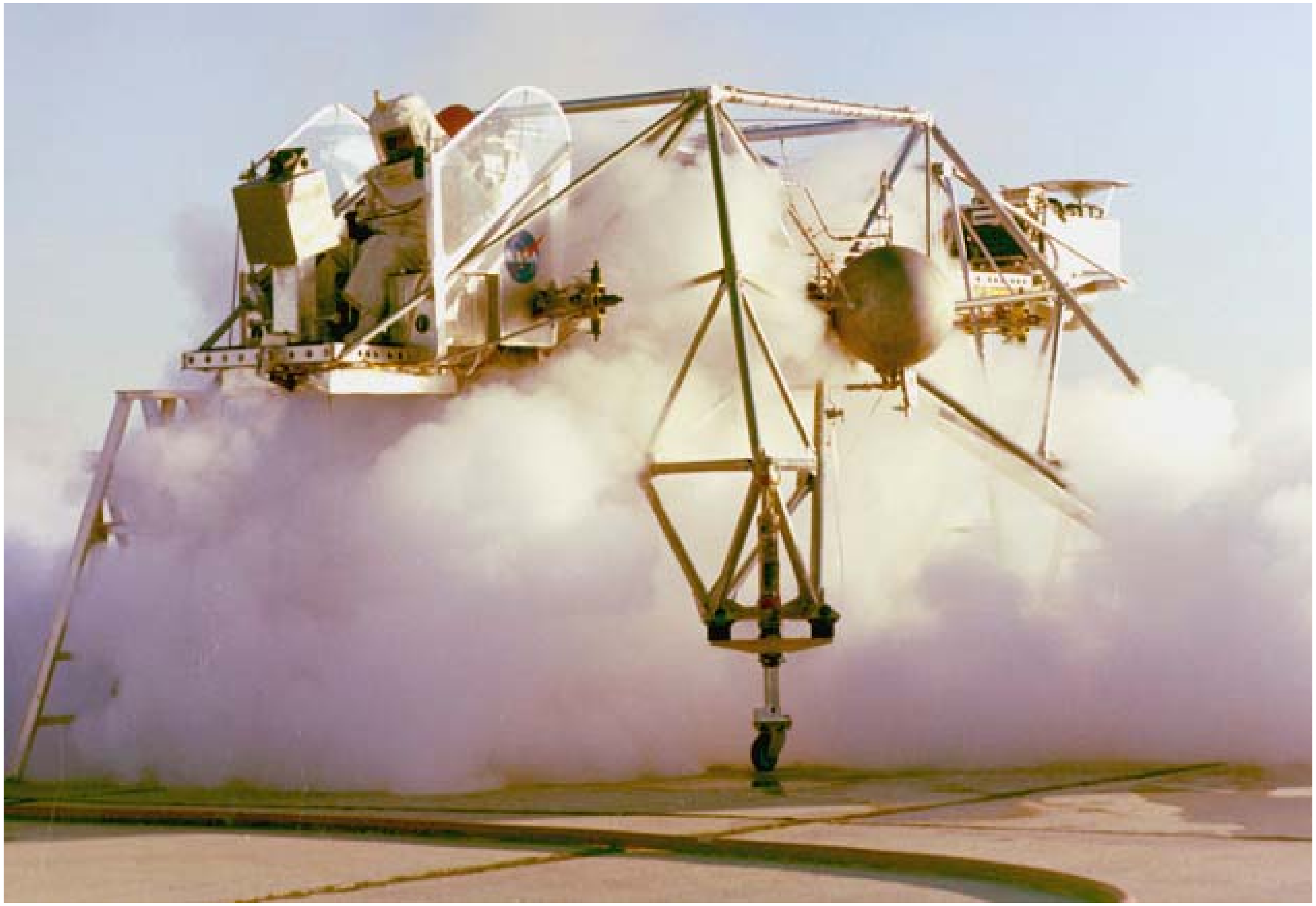
This Presentation is a collaboration of the following Apollo team members (Panel #1):

- Dean Grimm, NASA MSC LLRV/LLTV Program Manager
- Cal Jarvis, NASA FRC LLRV Controls Engineer
- Gene Matranga, NASA FRC Program Manager
- Warren North, NASA MSC Flight Crew Support Division Director, Mercury, Gemini, Apollo
- Wayne Ottinger, NASA FRC LLRV Project Engineer, Bell LLTV Technical Director
- Kenneth Szalai, NASA DFRC Director, 1990-1998 provided inputs on simulation and flight experience, including the PIO on Free Flight 5 of the Shuttle ALT Program and the F-8 PIO. Ken also provided **Simulation of the Subtle**, slides 9, 10, &11.

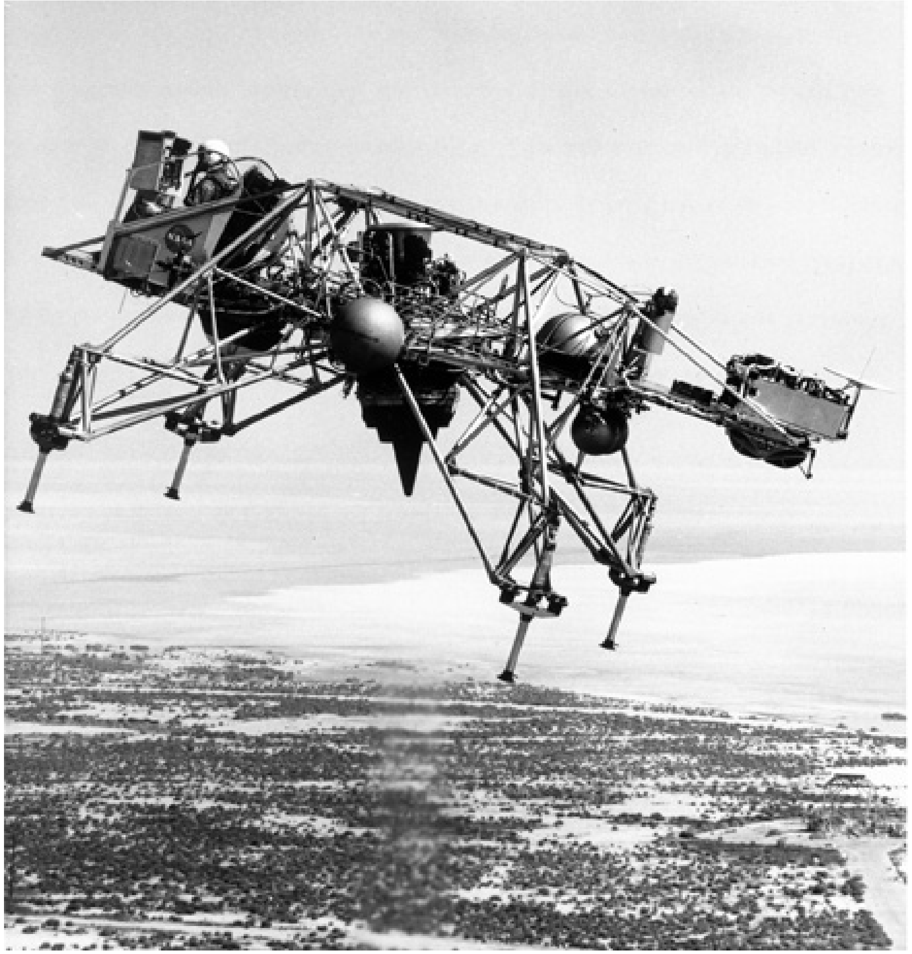
Part One: Presented by Matranga, North, & Ottinger

Part Two: Backup for discussions and archival.

LLRV Purging H_2O_2 Rocket System



LLRV no. 1 in lunar simulation mode. The center mounted jet engine is perpendicular to the Earth despite the LLRV's tilt angle. The jet engine supported 5/6 of the LLRV's weight,. Effectively simulating lunar gravity. (E-14570)



LLTV # 3, In Teague Auditorium Lobby at JSC

1. Apollo Lunar Landing Issues (LLRV/LLTV)
    a) LLRV Handling Qualities Flight Research Input to LM Flight Control System Design
    b) Manual Control for last several hundred feet
    c) Training required

2. Altair Lunar Landing Issues
    a) _______? Handling Qualities Flight Research Input to Altair Flight Control System Design
    b) Manual Control for last several hundred feet
    c) Training required

Three Major Issues for This Conference

1. Transition from Automatic Control to Manual for the final landing maneuver?
   a) Manual control, required as a backup, means training is crucial for success.
   b) When can manual takeover provide least-risk transients?
2. Training, fixed base simulators vs. free flight (LLTV)? Can the limitations of today's fixed base simulators (visual, VMS, ?) meet the needs based on the Apollo experience?
3. Are there unknowns such as scaling which are likely to impact flight control system design and piloting techniques on landing?
   a) Altair 3 times the weight of the LM
   b) 1.5 times the height
   c) 49 ft footprint to the LM's 29 ft
   d) Moments of Inertia

Other Issues

1. Are the cost-benefits of free-flight training worth it? (Several hundred feet altitude & 50 ft/sec horizontal ground speed for free-flight compared to less than 100 feet altitude and less than 25 ft/sec horizontal ground speed for fixed base technology?
2. Free-flight, make a safe landing or use the ejection seat, no reset button. A more stringent training syllabus.
3. Flight research experience has shown fixed base simulators need to be sped up to about 1.3 times real time to give realistic flight stress conditions.
4. PIO has been demonstrated not to be detected till flight. Some LLTV pilots experienced early PIO problems which were resolved as training matured.
5. STA experience on the Space Shuttle needs to be considered.

Simulation of the Subtle

1. The degree to which a given simulator provides the critical cueing and training for a specific configuration and task is difficult to gauge prior to operation of the actual flying vehicle. This is especially true in high-gain tasks or in conditions where there is little or no actual flight experience. One must also be aware that simulation, if missing some subtle feature, can provide negative training, as well.

2. The initial descents to the lunar surface were in this category. Lunar landings were unencumbered by aerodynamic uncertainties which are first order issues for vertical landing tasks in the atmosphere. But the combination of fuel reserve, landing area suitability, visual perception, and maneuvering in lunar gravity is especially challenging.

3. In addition to the training and familiarity that the LLTV provided to the Apollo Commanders in terms of rates, attitudes, and control dynamics, the LLTV must have provided calibration of fuel remaining, time remaining, and altitude intrinsically, in a way that was not simulated. This “calibration training” came with the LLTV simulation.

4. In the X-15 and lifting body simulations at the Flight Research Center in the 60's, it was found that apparent time was faster in flight than it was in the fixed base simulator:

Excerpt from **SP-4220 Wingless Flight: The Lifting Body Story**

In his book **At the Edge of Space**, Milt Thompson discussed how this difference between simulator seconds and seconds as perceived by pilots in actual flight was first discovered during the X-15 program.

"Regardless of how much practice we had on the simulator, we always seemed to be behind the airplane when flying the real flight. We could not easily keep up with the flight plan…..Jack Kolf came up with the idea of a fast time simulation, wherein we compressed the time in the simulator to represent the actual flight. This technique seemed to make the simulation more realistic."

5. The <lifting body> pilots were unanimous in reporting that, once in flight, the events of the mission always seemed to progress more rapidly than they had in the simulator.
6. As a result, engineers and pilots experimented with speeding up the simulation's integration rates, or making the apparent time progress faster. They found that the events in actual flight seemed to occur at about the same rate as they had in the simulator once that simulation time was adjusted so that 40 simulator seconds was equal to about 60 "real" seconds. Only the final simulation planning sessions for a given flight were conducted in this way.
7. The calibration of the ground simulator was done on the basis of actual flight experience in the case of the X-15 and lifting body programs.
8. For an as-yet to be flown vehicle and mission such as the lunar landings, a free flight simulator provided inherent time and distance calibration, since the consequences of fuel exhaustion were nearly the same for the LLTV mission as for the LM landing.

K. Szalai 2-21-2008

Summary of Armstrong/Conrad Comments on Lunar Landing Training Requirements

1. Factors that Contributed to High Level of Confidence:
   a) Knowledge/experience of physiological effects and sensations of large pitch and roll maneuvers during translations near lunar surface.
   b) Large number of realistic, high fidelity landing simulations as close to actual mission as possible. (Same basic approach used in developing confidence for checkout in any new aircraft).
   c) No replacement for training in dynamic vehicle from 200 feet to touchdown. (500 feet even more desirable).

Summary of Armstrong/Conrad Comments on Lunar Landing Training Requirements

1. Requirements For Establishing adequate level of Confidence:
    a) Imperative to train with in-flight landing simulator as close to actual mission time as possible.
    b) In flight simulation of transition from landing trajectory to hover at 500 feet is required for adequate landing sight recognition and basic flying.
    c) Dynamic motion simulation necessary to enhance confidence level below 500 feet to touchdown especially if unplanned transition is required.
    d) In-flight simulation training important in developing physiological relationships and sensations between pitch/roll attitude and vehicle translations in lunar gravitational environment.

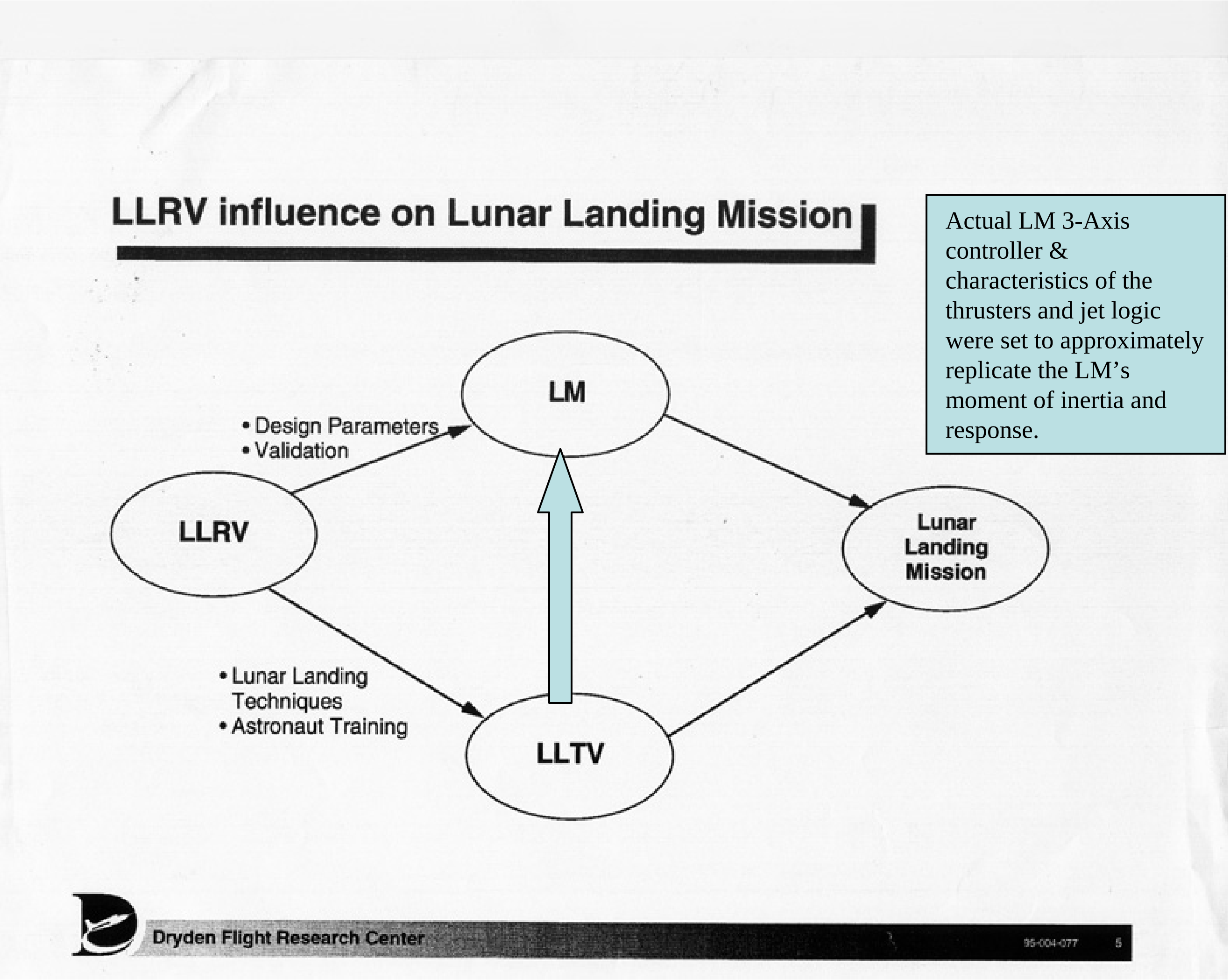
Summary of Armstrong/Conrad Comments on Lunar Landing Training Requirements

1. Mission Success for Landing Maneuver based on “No Mistakes Criteria” for “First” Landing. Critical Factors Include:
   a) Always a new pilot, i.e. always landing for first time.
   b) Always a new unknown landing site/terrain.
   c) Each mission generally more difficult than previous landings in terms of area, terrain, surface environment, etc.
   d) The more difficult the landing site, the greater the “level of confidence” required.
   e) Landing on instruments requires even greater “level of confidence factor” (errors inherent in inertial system updates & errors in the update program device and the radar altimeter were of significant concern .

Overall Summary of LLRV/LLTV Program

1. Extensive effort was required throughout the 11 years of the LLRV/LLTV programs to first obtain, and then sustain, both technical and financial support.
2. The Apollo training requirements were substantially compromised due to:
   a) Lack of adequate planning
   b) Recognition of the lead times and complexity of the vehicle design infrastructure required to support flight operations.
   c) Lack of adequate training of flight operations personnel to conduct safe flight operations outside of the flight research environment at FRC.
3. In spite of the above handicaps, the research results made essential contributions to the LM design. The astronaut training did make a key contribution to the success of all six lunar landings. All were made under manual control, with positive feedback from the astronauts about the quality of the LLTV flight training in its representation of the real landing experiences.

Overview of the LLRV Program



LLRV influence on Lunar Landing Mission

Actual LM 3-Axis controller & characteristics of the thrusters and jet logic were set to approximately replicate the LM's moment of inertia and response.

LM

- Design Parameters
- Validation

LLRV

Lunar Landing Mission

- Lunar Landing Techniques
- Astronaut Training

LLTV

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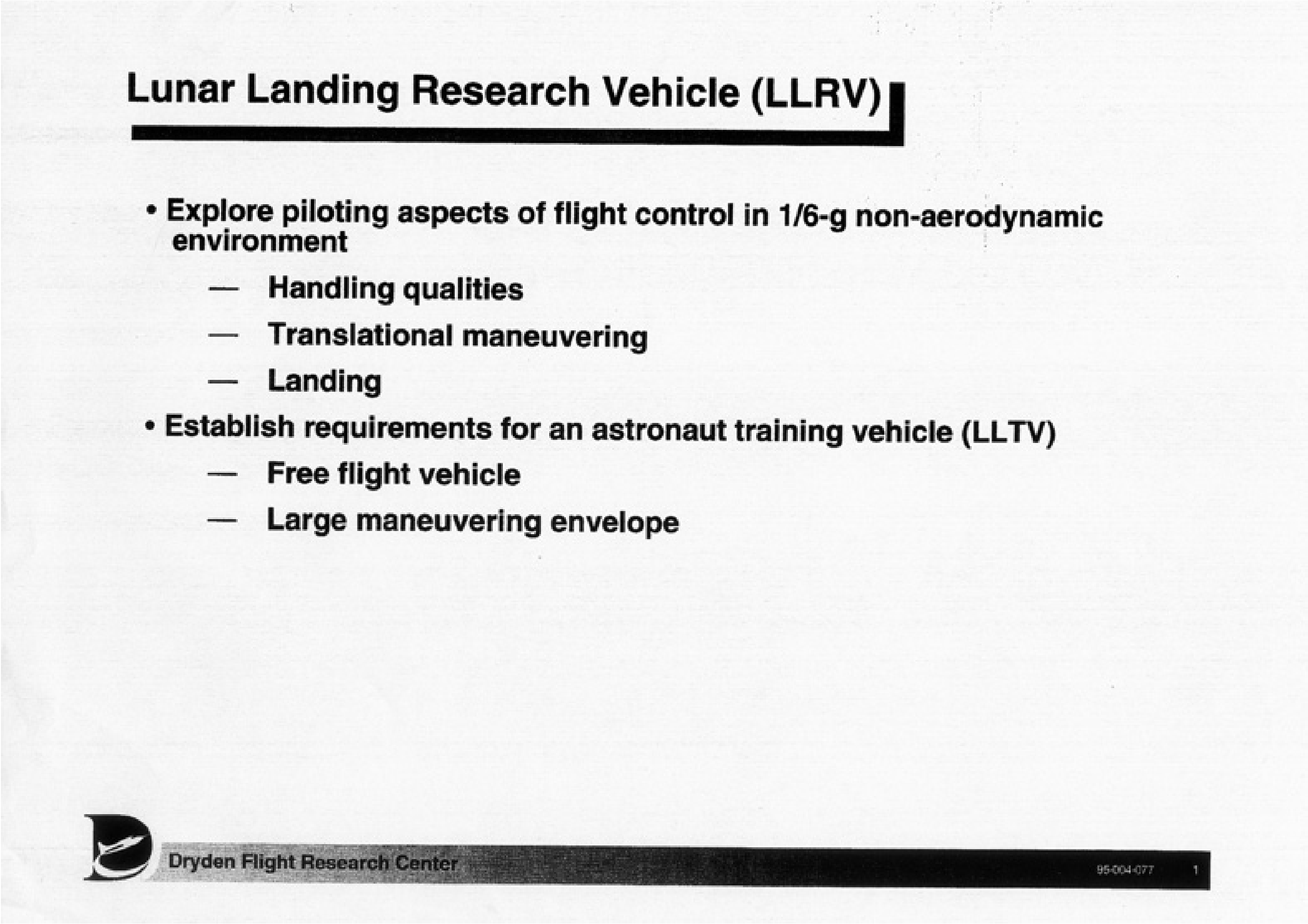
Overview of the LLRV Program



Lunar Landing Research Vehicle (LLRV)

- Explore piloting aspects of flight control in 1/6-g non-aerodynamic environment
  - Handling qualities
  - Translational maneuvering
  - Landing
- Establish requirements for an astronaut training vehicle (LLTV)
  - Free flight vehicle
  - Large maneuvering envelope

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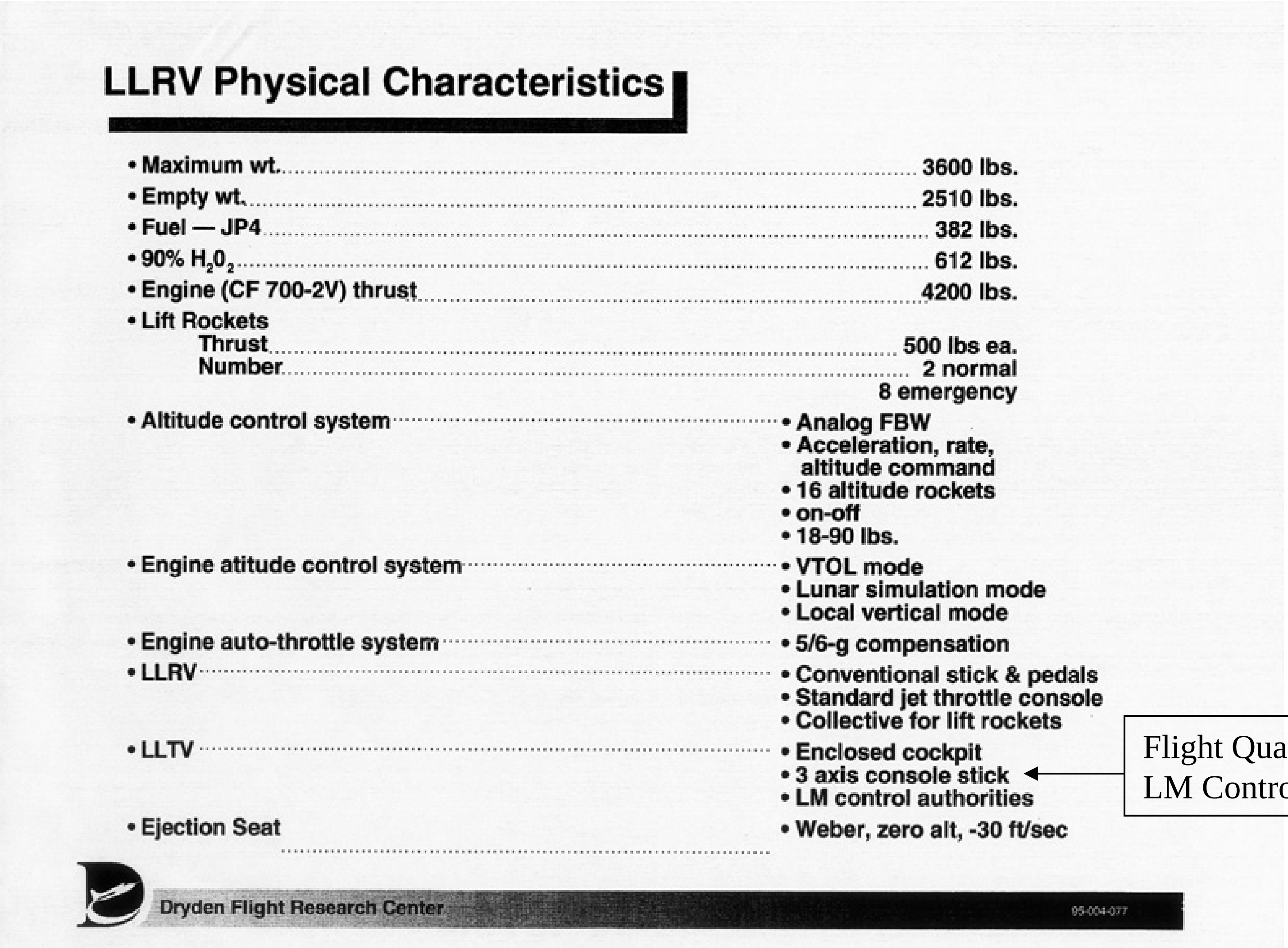
Overview of the LLRV Program



LLRV Physical Characteristics

• Maximum wt.	3600 lbs.
• Empty wt.	2510 lbs.
• Fuel — JP4	382 lbs.
• 90% H_20_2	612 lbs.
• Engine (CF 700-2V) thrust	4200 lbs.
• Lift Rockets	
Thrust	500 lbs ea.
Number	2 normal 8 emergency
• Altitude control system	• Analog FBW • Acceleration, rate, altitude command • 16 altitude rockets • on-off • 18-90 lbs.
• Engine atitude control system	• VTOL mode • Lunar simulation mode • Local vertical mode
• Engine auto-throttle system	• 5/6-g compensation
• LLRV	• Conventional stick & pedals • Standard jet throttle console • Collective for lift rockets
• LLTV	• Enclosed cockpit • 3 axis console stick • LM control authorities
• Ejection Seat	• Weber, zero alt, -30 ft/sec

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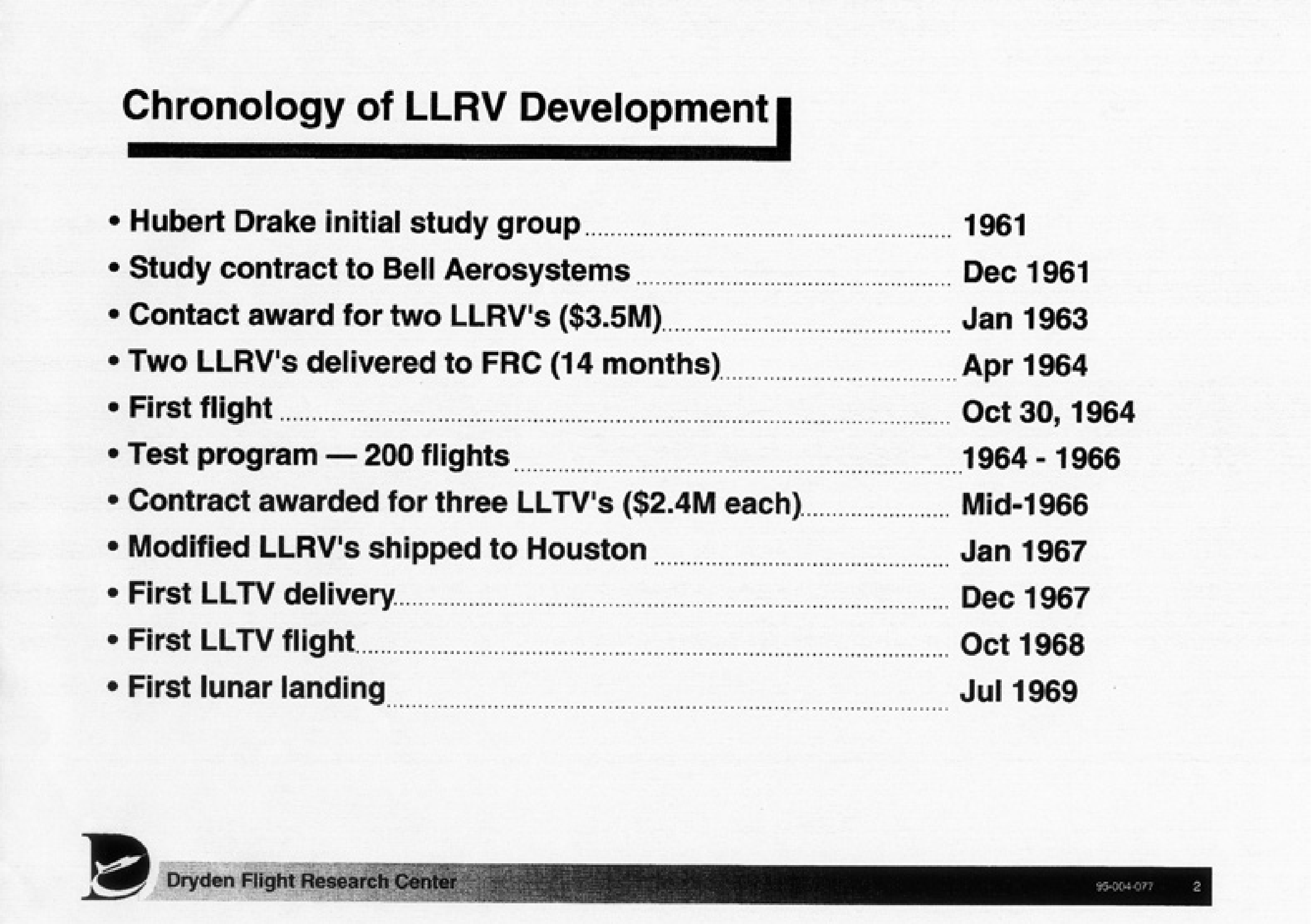
Flight Qualified
LM Controller

Overview of the LLRV Program



Chronology of LLRV Development

• Hubert Drake initial study group	1961
• Study contract to Bell Aerosystems	Dec 1961
• Contact award for two LLRV's ($3.5M)	Jan 1963
• Two LLRV's delivered to FRC (14 months)	Apr 1964
• First flight	Oct 30, 1964
• Test program — 200 flights	1964 - 1966
• Contract awarded for three LLTV's ($2.4M each)	Mid-1966
• Modified LLRV's shipped to Houston	Jan 1967
• First LLTV delivery	Dec 1967
• First LLTV flight	Oct 1968
• First lunar landing	Jul 1969

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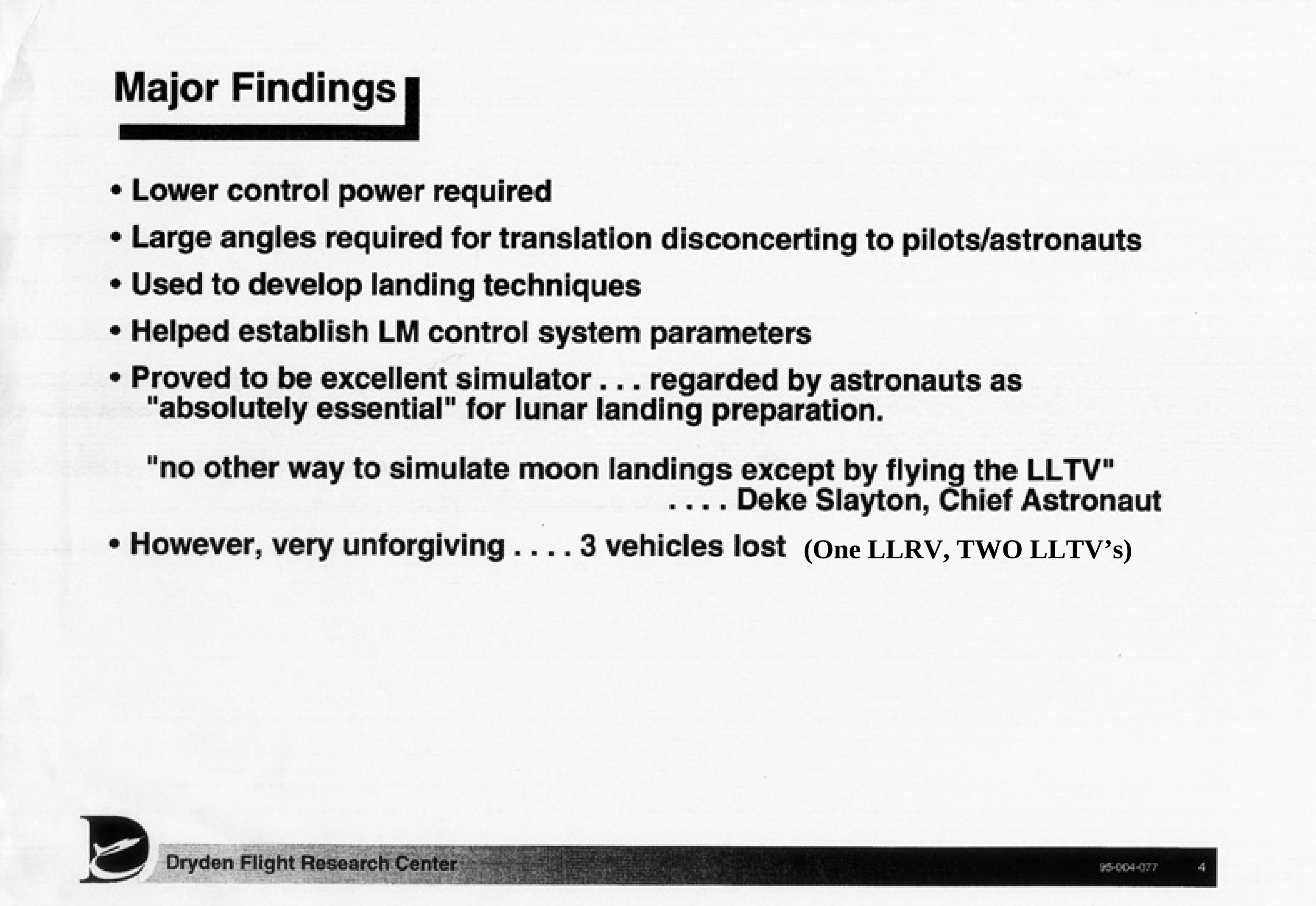
Overview of the LLRV Program



Major Findings

- Lower control power required
- Large angles required for translation disconcerting to pilots/astronauts
- Used to develop landing techniques
- Helped establish LM control system parameters
- Proved to be excellent simulator . . . regarded by astronauts as "absolutely essential" for lunar landing preparation.

  "no other way to simulate moon landings except by flying the LLTV"
  . . . . Deke Slayton, Chief Astronaut
- However, very unforgiving . . . . 3 vehicles lost **(One LLRV, TWO LLTV's)**

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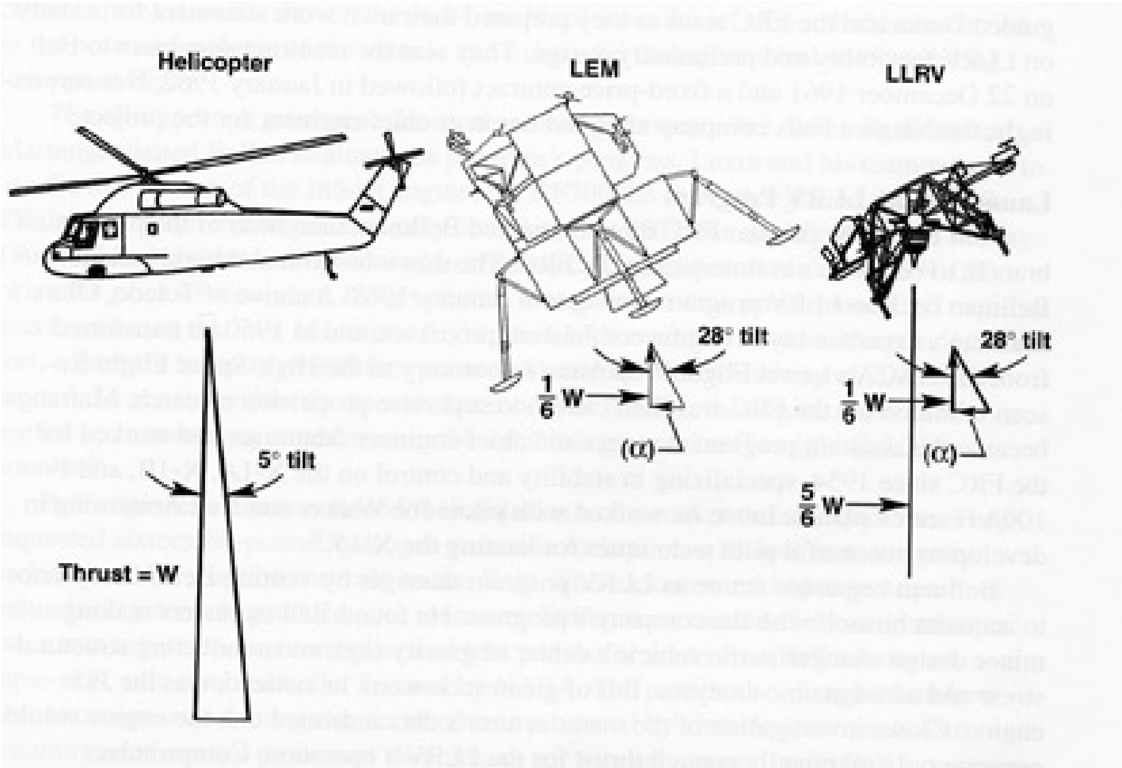
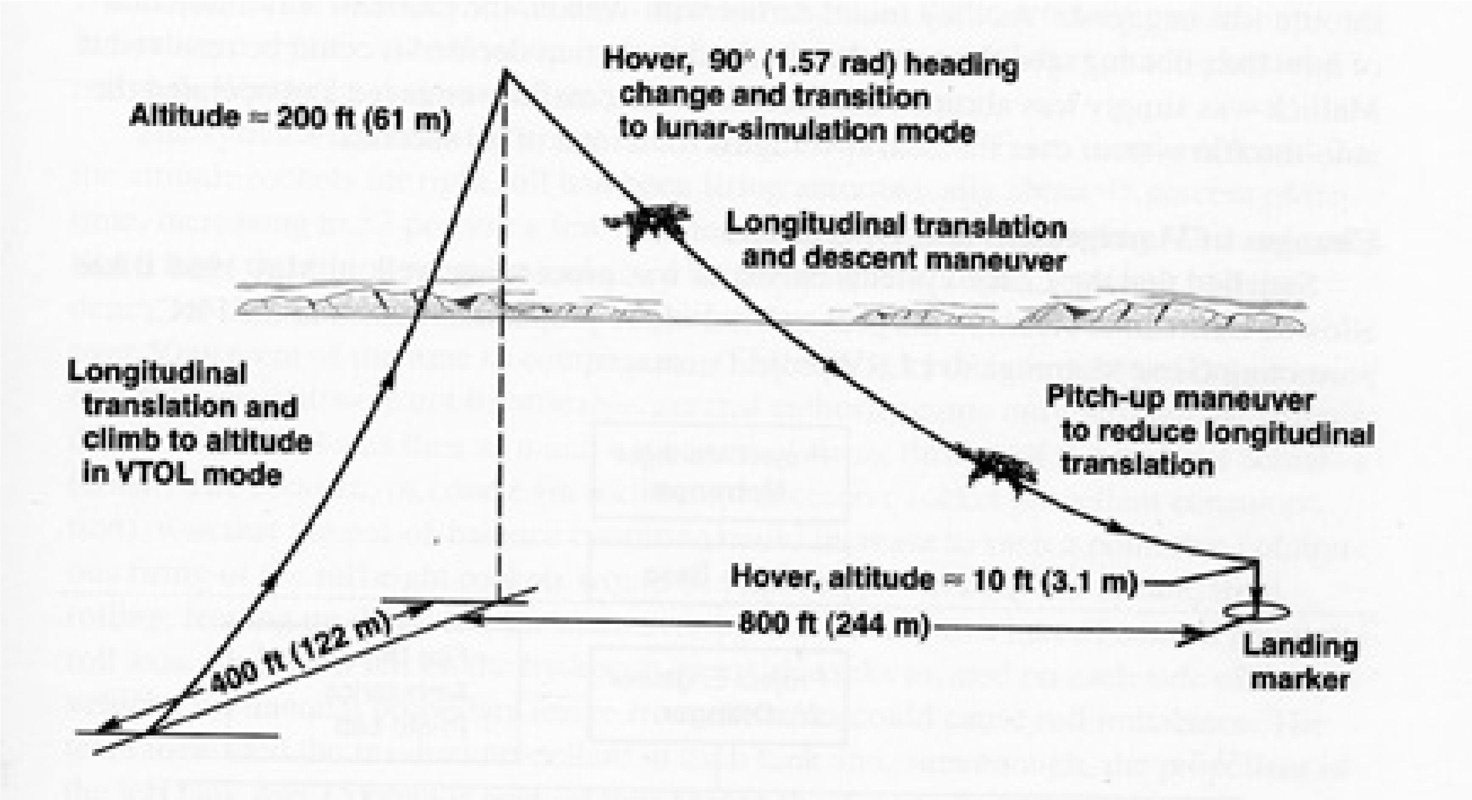
Helicopters Cannot Do the Free-Flight Simulations

Horizontal Translations

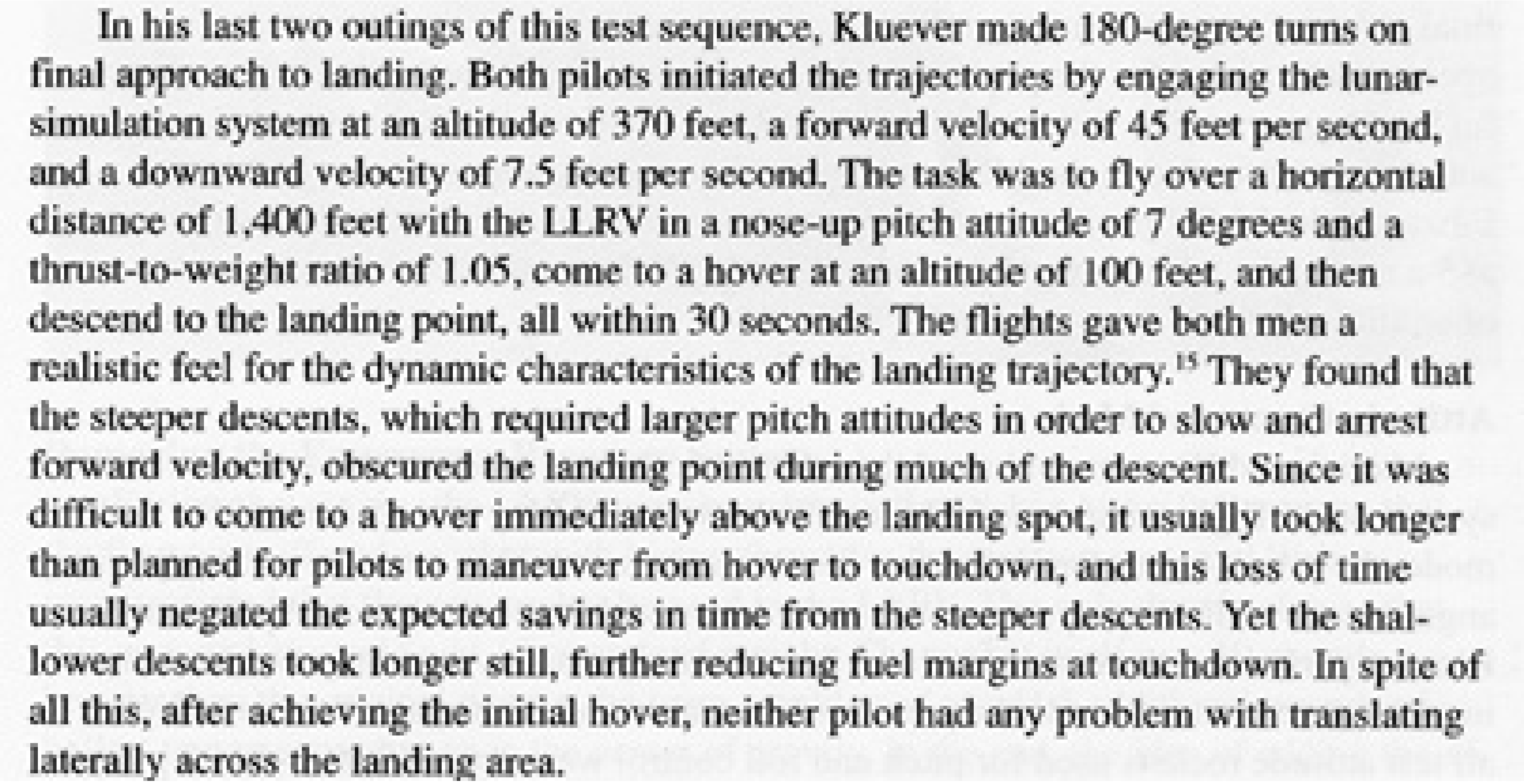


This drawing illustrates the hovering tilt angle capabilities of the SH-2 helicopter and LLRV compared to the Lunar Module (LM). The LLRV/LLTV, with its gimbaled engine, was able to more accurately simulate the performance of the LM by approximating lunar gravity, which is 1/6 that of Earth.

An early diagram of an optimal lunar landing trajectory, which the LLRV was capable of simulating.



Actual LLRV Trajectories Flown (Page 111 of Monograph NASA SP-2004-4535 Unconventional, Contrary, and Ugly: The Lunar Landing Research Vehicle

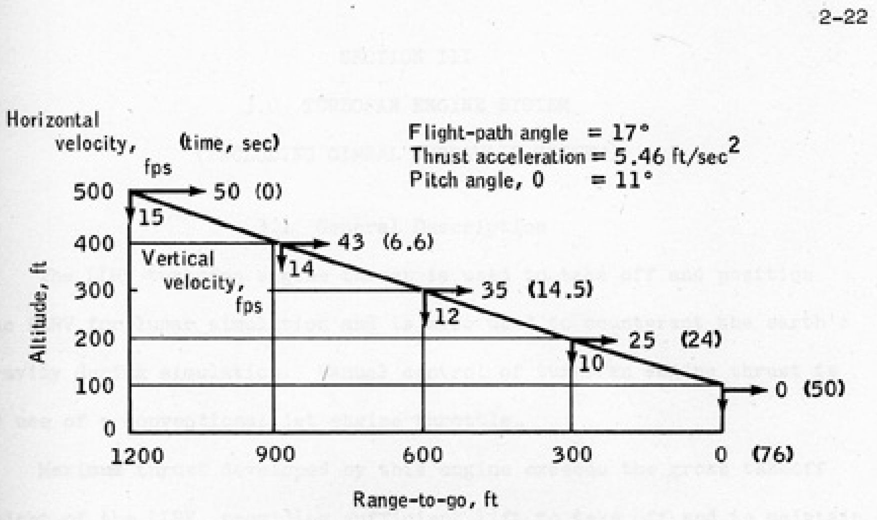


In his last two outings of this test sequence, Kluever made 180-degree turns on final approach to landing. Both pilots initiated the trajectories by engaging the lunar-simulation system at an altitude of 370 feet, a forward velocity of 45 feet per second, and a downward velocity of 7.5 feet per second. The task was to fly over a horizontal distance of 1,400 feet with the LLRV in a nose-up pitch attitude of 7 degrees and a thrust-to-weight ratio of 1.05, come to a hover at an altitude of 100 feet, and then descend to the landing point, all within 30 seconds. The flights gave both men a realistic feel for the dynamic characteristics of the landing trajectory.[15] They found that the steeper descents, which required larger pitch attitudes in order to slow and arrest forward velocity, obscured the landing point during much of the descent. Since it was difficult to come to a hover immediately above the landing spot, it usually took longer than planned for pilots to maneuver from hover to touchdown, and this loss of time usually negated the expected savings in time from the steeper descents. Yet the shallower descents took longer still, further reducing fuel margins at touchdown. In spite of all this, after achieving the initial hover, neither pilot had any problem with translating laterally across the landing area.

LLTV Trajectory for Lunar Simulation

<u>Neil Armstrong:</u> I'm talking of 50 feet per/sec. over the ground which is the transition phase. That phase from breaking where you are essentially, just watching out the window and pre-designating and doing those things, to come into a hover. **<u>That's the 150 feet per/sec. to 10 feet per/sec. region --that's where you really have a lot of flying.</u>**

<u>From LLTV Flight Manual</u>



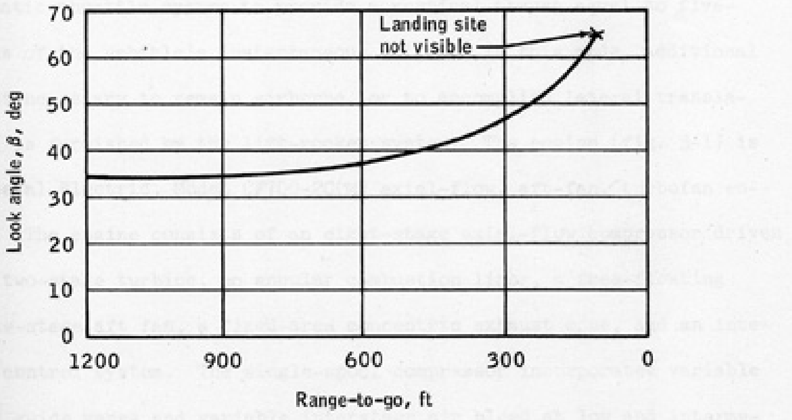
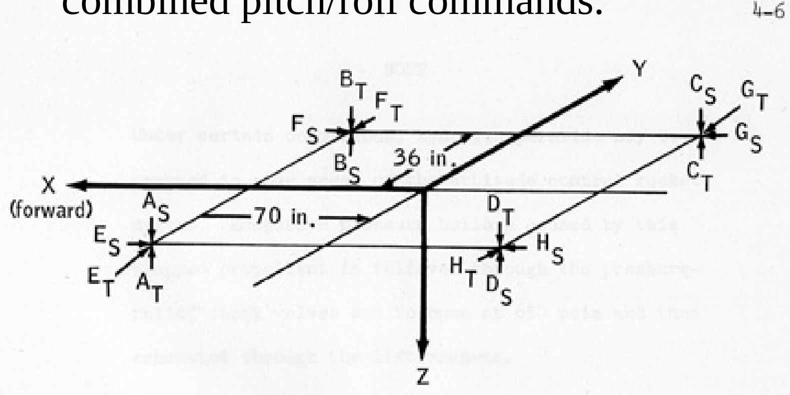


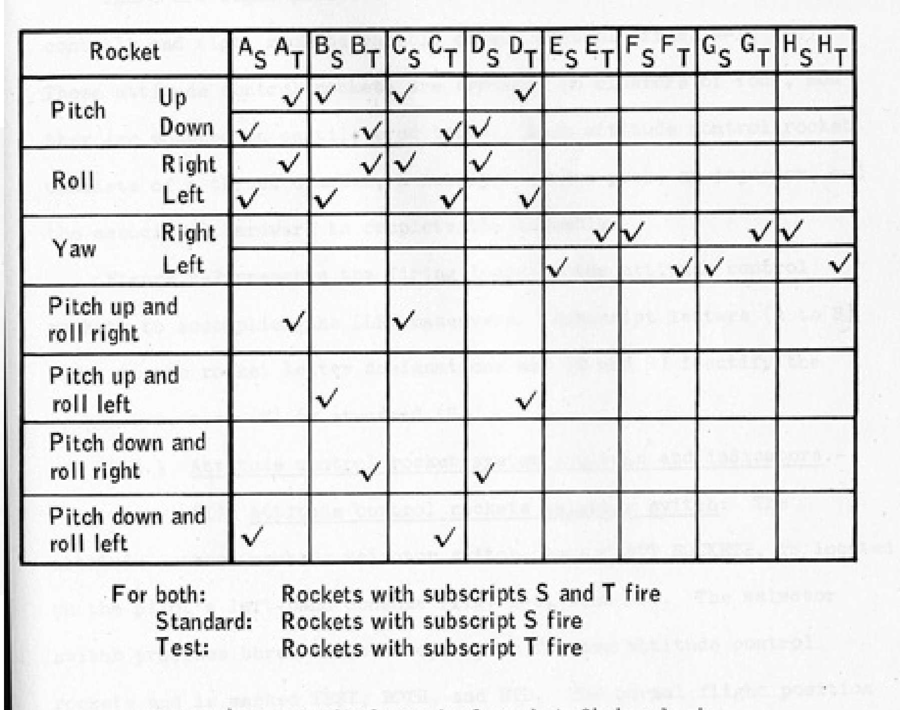
Figure 2-9.- Typical lunar module trajectory characteristics for final landing phase.

Attitude Control System Firing Logic

The firing logic for the LLRV is shown here, it is different from the LM as the LM attitude rockets were mounted in between the legs. This did not significantly affect the simulation performance for the research program, however, the LLTV logic was changed to match the LM's. Redundant ACS rocket systems of 8 rockets each had to be controlled so all pitch, roll, and yaw commands could be accomplished with one of the ACS systems failed.

The LLTV logic resulted in some loss of control authority in certain flight conditions as only one rocket would fire in combined pitch/roll commands.





Rocket		A_S	A_T	B_S	B_T	C_S	C_T	D_S	D_T	E_S	E_T	F_S	F_T	G_S	G_T	H_S	H_T
Pitch	Up		✓	✓		✓			✓								
	Down	✓			✓		✓	✓									
Roll	Right		✓		✓	✓		✓									
	Left	✓		✓			✓		✓								
Yaw	Right										✓	✓			✓	✓	
	Left									✓			✓	✓			✓
Pitch up and roll right			✓			✓											
Pitch up and roll left				✓					✓								
Pitch down and roll right					✓			✓									
Pitch down and roll left		✓					✓										

For both: Rockets with subscripts S and T fire
Standard: Rockets with subscript S fire
Test: Rockets with subscript T fire

Figure 4-2.- Attitude control rocket firing logic.

Summary/Recommendations
(From the Apollo LLRV/LLTV Engineering Legacy Team

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1. NASA’s Altair Project should consider forming a task group, led by a designated NASA center, to engage industry, academia, other NASA centers, and Apollo legacy team members to: **Perform comparative studies including realism of simulations and costs for the full spectrum of simulation technologies, including free flight, for both**:
a) Design/development support of Altair flight systems
b) Astronaut training

2. Utilize the results of this conference to formulate a plan for the task group considering the early benefits and impacts to overall program schedule and funding requirements. (expediting the completion of such a study will influence significant program definitions early).

3. Evaluate the risks, applying the lessons learned from Apollo, of free-flight operations for both research and training compared to the risks of utilizing only fixed-base and moving-base simulators for future lunar landings. Compare the costs of "insuring" success between free-flight simulation supplemented by fixed-base and moving-base technologies to that without any future free-flight simulations.