Apollo

GNC & Pilot Interface (Pilot-in-the Loop) Lunar Simulations in Free Flight

LLRV

LLTV

Recommendations for Altair Guidance, Navigation & Control (GNC) Development and Astronaut Training for Lunar Landings

- ***Selection Process for a Free Flight Simulation Platform***
- ***Optimizing Safety, Cost, and Performance: a Broad View***
- ***Justification for a Free Flight Lunar Simulation Platform***

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Notable changes:

Page 1, 1st paragraph, added pilot interface (as well as numerous other locations) and footnote
Page 2 1st paragraph, added 2 bullets
Page 9 3.4 1st paragraph, replaced "large drogue chute" with "large Cirrus type (light aircraft ballistic recovery system) chute"
Pages 13-18, added Apollo Commander Comments

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1. EXECUTIVE SUMMARY

NASA Johnson Space Center (JSC) Altair Lunar Lander Project Office (LLPO) has given NASA Dryden Flight Research Center (DFRC) a trade study task to evaluate available free-flying vehicle concepts for support of Altair astronaut training which will be examined for selection, presently scheduled for early 2009. The use of this Altair free-flight trainer for GNC flight test validation and development of pilot interface concepts was not part of the task assignment, but will be considered in the final evaluation.[2] The key issues to be considered in this selection process, with emphasis on the advantages of the gimbaled jet concept validated by Apollo, are presented in this white paper. The gimbaled jet concept will:

1. Use today's readily available technologies proven in numerous aircraft, launch vehicles and satellites and provide the best available earth-bound lunar simulation for a free-flight platform.
2. Be cost competitive with any modified VTOL configuration (designed to meet only a fraction of the critical requirements): modified VTOLs (including rotorcraft) cannot provide rocket reaction control systems (RCS) that are required to provide the response time needed for accurate simulation of the spacecraft with accurate aerodynamic drag compensation (no active feedback isolating drag forces or effects of gusts) particularly needed for GNC flight test validation and to prevent negative training due to invalid vehicle attitudes. Only the Aircrane/gimbaled cab can provide de-coupled 5/6th g in both pitch and roll, but may come up short on the drag and gust compensation and cannot perform reaction control simulation. Other optional platforms are only applicable to the final vertical descent portion of the trajectory requirements.
3. Provide design to task for both GNC development and training using the proven Apollo performance capabilities for earth bound lunar landing simulation, while meeting all simulation and training requirements.
4. Provide superior safety and reliability, particularly for crew survivability via ejection seats, neither possible for rotorcraft nor available on existing tilt-rotor vehicles. Only the Harrier and the LLRV and LLTV provide ejection seats.
5. Maximize the Return on Investment (ROI) benefits of early buy down of risk by planning now for integrated flight test of GNC systems with the pilot in the loop starting at least six months before PDR for Altair. NASA needs to simultaneously define GNC development and training requirements to provide the most efficient free flight lunar simulation facility at the lowest cost.

NASA should accelerate the selection process for the choice of a free flight platform to fully realize the development and training benefits to the Altair program. A timely finalization of the selection process will provide adequate lead time for finalizing feasibility and cost studies leading to procurement of long lead items, using Altair PDR and CDR target dates and GNC development requirements (can't start too early). Desktop simulations can provide early confirmations of the performance comparisons of the six options. Thus, emphasizing the need for completing the cost estimation under NASA sponsorship of the gimbaled jet solution.

DFRC Altair LLTV Proposed Requirements: A panel of Apollo and active astronauts and other contemporary experts should be formed now and scheduled now to meet in late 2008 to develop a consensus for the weighting factors to be used in the selection process.

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[2] The Apollo LLRV performed flight research in the very early stages of the LM design and made significant contributions to the LM flight control system and pilot interface solutions.

2. BACKGROUND/TODAY'S STATUS

2.1. Apollo Legacy

In 1962, the genius of the *gimbaled jet approach* to free flight earth-bound lunar simulation matured into the Lunar Landing Research and Training Vehicle Programs. The six piloted Apollo landings confirmed the fidelity of the earth-bound simulations that was provided by the gimbaled jet concept. The LLRV made valuable contributions to the Apollo Lunar Module (LM) in a number of critical areas as the early LM design was getting started:[3]

- Control system design, i.e., determining the lowest acceptable control authority for the attitude control system, acceptable vehicle angular attitude rates and attitude accelerations rates.
- Pilot interface issues, including cockpit displays, controls layout, pilot's field of view.

This foundation provided by the LLRV transformed into the LLTV which provided valuable training for all Apollo mission commanders and backup commanders. This was accomplished using 1960's motion sensors including rate gyros, vertical gyros, and accelerometers arranged in a clever symmetrical and duplicate pattern around the center of gravity. These sensors, when combined with the analog electronics available at the time, provided 0.005g accuracy in canceling out the earth's 5/6th g component and the aerodynamic forces acting on the vehicle. Figure 2-1 compares the gimbaled jet simulation accuracy to that of an un-gimbaled VTOL platform. The use of reaction control rockets for attitude control and lift in combination with the gimbaled jet for aero drag and the 5/6th g compensation provided excellent correlation with the LM flight, handling/response and performance characteristics, as shown in a recent desktop simulation performed by Orbital Sciences (Figure 2-1).

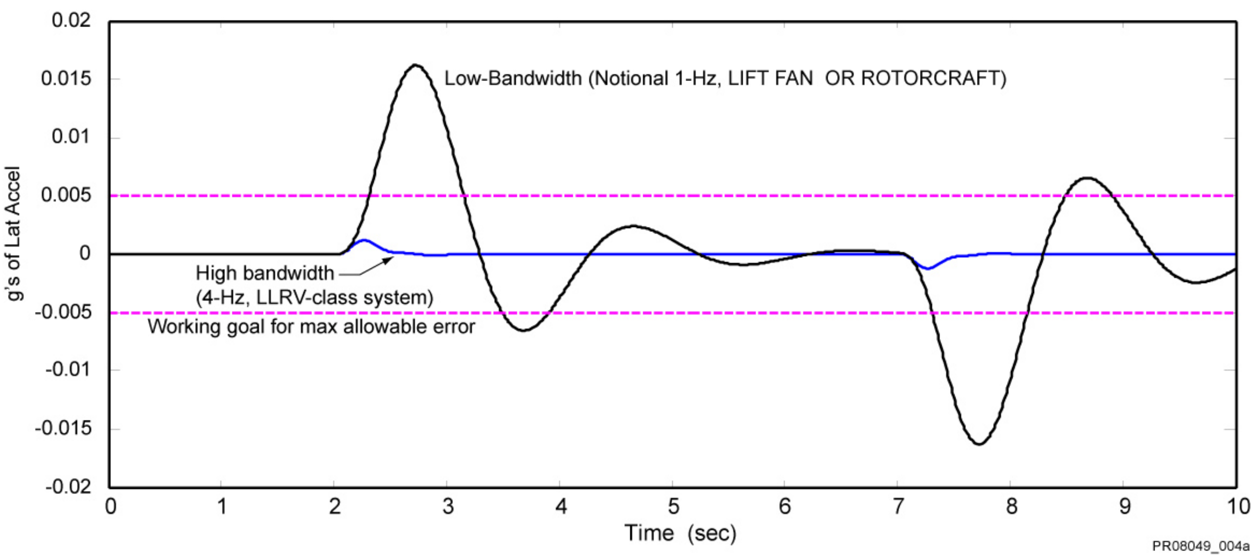


Figure 2-1. Handling Qualities Error for Low-Bandwidth (VTOL-Type) Gimbaled System vs. High Bandwidth Gimbaled System

[3] http://www.history.nasa.gov/alsj/LLRV_Monograph.pdf

Figure 2-2 shows the 1963 design solution to enabling the LLRV to perform in free flight as though it were in a lunar gravity field as well as flying in a vacuum, thus achieving as close to a lunar simulation on the earth as possible.

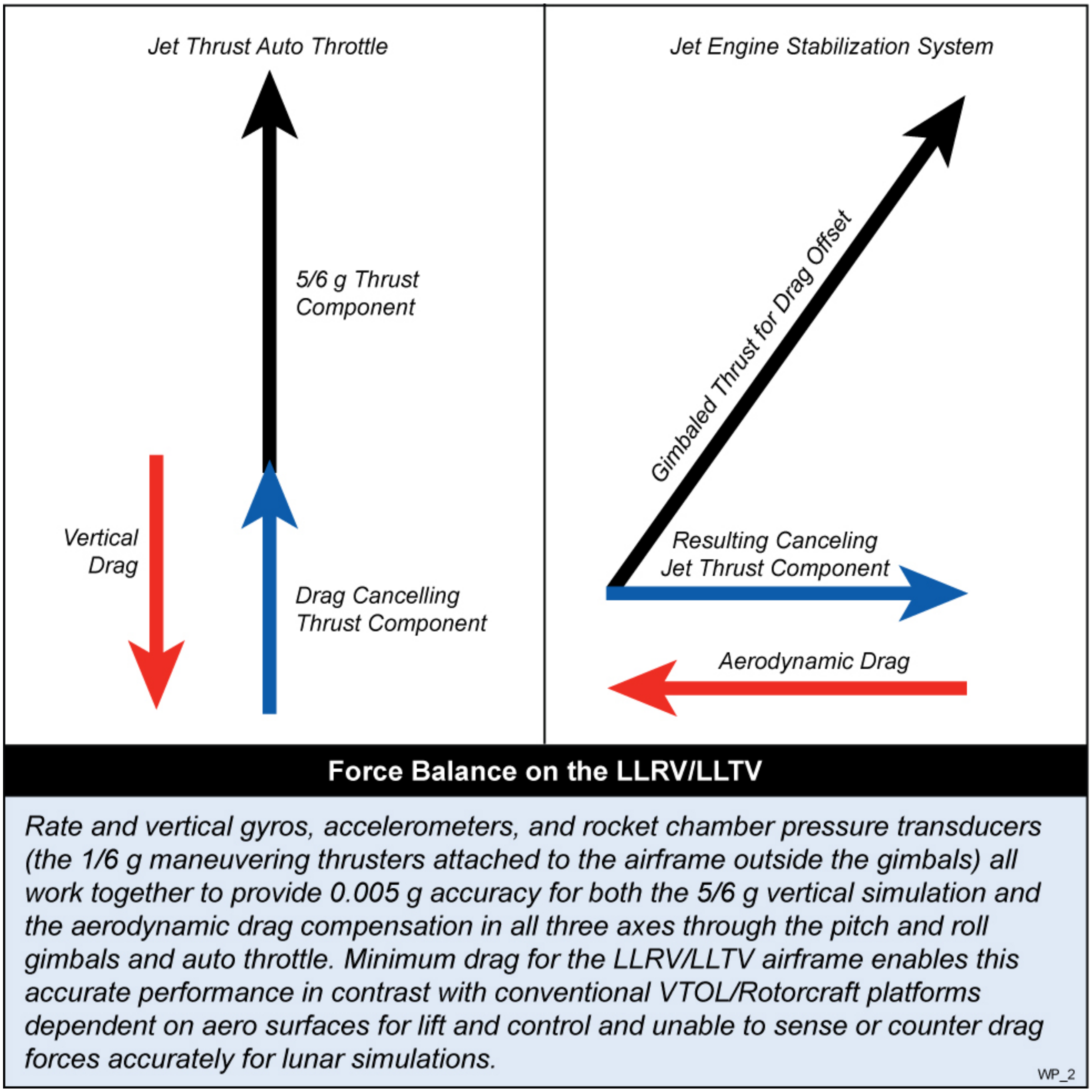


Figure 2-2. The Genius of Bell Aerosystem's (Walt Rusnak) 1963 Design of the Gimbaled Jet Lunar g and Aerodynamic Drag Compensation System

The residual perception of the LLRV/LLTV as being a dangerous vehicle to fly exists today and this should be re-evaluated, in depth, beyond a first impression. There were 795 successful flights conducted at both the NASA Flight Research Center and Ellington Field. There were three accidents and aircraft losses, but no pilot was significantly injured. The basic design of the LLRV/LLTV included a better than zero-zero ejection system. This was due to the environment that the vehicles operated in and the unique aircraft systems that were required to provide the lunar simulation. Vehicle losses in two of the three accidents were attributed to human error (not pilot but ground crew--Crew Resource Management errors) and are preventable with proper CRM and integrated systems monitoring and displays. The third accident was due to an upgrade in the DC generator of the jet engine which resulted in a high residual magnetic field upon failure, preventing switchover to the emergency electrical bus. This could have been easily prevented with a design correction or modern battery technology.

The success of the LLRV/LLTV in the Apollo Program is well documented and noted. The vehicles that achieved this free flight simulation were unique and complex because of the nature of their mission. Much data was gathered and many lessons learned in their operation. The LLRVs and LLTVs as the first fly-by-wire aircraft as well as in a VTOL configuration were operating with exceptional safety and reliability records during the time when tragic T-38 fatal accidents and helicopter crashes plagued the Apollo program (Figure 2-3).

2.2. March 2008 Go For Lunar Landing Conference [4]

The predominate view of the conference participants and representatives of the Apollo astronaut, engineering and program management team was that a free flyer was needed for Altair, particularly for GNC development as well as astronaut training. The question was raised for use of a modified VTOL platform performing the free flight earth-bound lunar simulation. One answer questioned the response time of existing VTOL systems to satisfy the requirements of the Altair. Only one Apollo astronaut who trained on the LLTV (but never landed on the moon) reported that he felt that the free flight simulation for Altair would not be needed. Another, who did land on the moon, felt the training could be accomplished for Altair with current fixed or motion based simulators and that a free flight simulator would not be needed. The other seven astronauts have expressed support for the free flight training as a valuable contribution to their preparedness for successfully piloting and landing the LM. The Space Shuttle, F-8 Digital Fly-by-Wire, F-22, and the LLTV as well as other aircraft have all experienced pilot induced oscillations (PIO) in actual flights that were undetected in fixed or moving base simulators. This is a strong justification for astronauts to train in a free flight simulator before attempting an actual lunar landing.

As part of the Apollo team presentation, the history and contributions from the LLRV and LLTV were presented. [5, 6] A summary of that presentation is given here.

<u>Slide 12 (Part One)</u> – **Summary of Armstrong/Conrad Comments on Lunar Landing Training Requirements**

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.)

[4] http://www.lunarlanding.info/articles/GoReportVersion1.13.pdf

[5] http://www.lunarlanding.info/articles/GOFORLL_lores-part_one_conf_2_25.pdf

[6] http://www.lunarlanding.info/articles/GOFORLL_lores_part_two_conf_2_25.pdf

c) No replacement for training in dynamic vehicle from 200 feet to touchdown (500 feet even more desirable).

Slide 13 (Part One)
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.

Slide 14 (Part One)
Mission Success for Landing Maneuver based on "No Mistakes Criteria" for "First" Landing. Critical Factors Include:

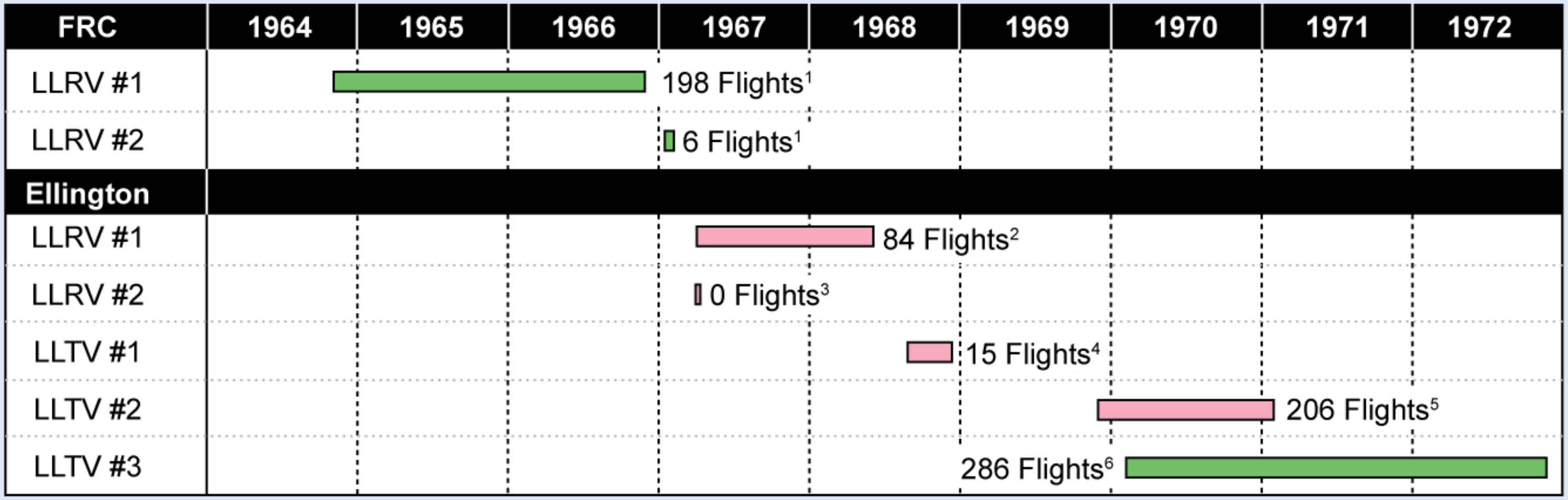
a) Always a new pilot, i.e. always landing for first time.
b) Always a new unknown landing site/terrain.
c) Each mission generally more difficult than previous landings in terms of area, terrain, surface environment, etc.
d) The more difficult the landing site, the greater the "level of confidence" required.
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.

2.3. NASA's JSC Lunar Lander Project Office

The decision has not been made as to the firm requirement for a free flight trainer, however in case that requirement does materialize, LLPO is looking at options. In May, 2008, NASA DFRC was assigned a task to perform a trade study for an Altair Lunar Landing Training Vehicle. Six candidates are being studied currently, including:

- The gimbaled jet free flyer, updated from Apollo, being studied by Orbital Sciences Corporation.
- A variable stability Blackhawk helicopter.
- Tilt-rotor vehicles, such as the BA-609 and the V-22.
- A variable stability Harrier, such as the VAAC Harrier.
- An Erickson S-64F Aircrane with a gimbaled pod.
- A sport or acrobatic helicopter.

An interim report is planned in late September, 2008. No formal consideration of a free flight lunar simulation platform for GNC and pilot interface development has been made that is evident to date. It is likely that the LLPO is contemplating the acquisition and development costs for a gimbaled jet similar to Apollo will be many times more expensive than a modified VTOL.



1. *No Accidents*
2. *Flight Ops Human Error; __**Armstrong**__; CRM failure to communicate; loss of attitude control; ejection; bit his tongue*
3. *After LLRV#1 crash, decision made to go to LLTVs*
4. *Flight Ops Human Error; __**Algranti**__; wind shear; loss of attitude control; ejection; minor leg injury; Ellington CRM from 4 to 40 people after this accident*
5. *__**Stu Present**__; DC generator/switchover failure; ejection; no injuries - Supported Apollo 11, 12 and 13*
6. *Supported Apollo 14, 15, 16, 17, no accidents*

NASA Monograph, NASA SP-2004-4535, Pg. 120
In turn, Matranga mentioned his concern about the operating rules the MSC had set for the LLRVs and LLTVs at Houston, particularly the 30-knot wind limit, which was twice the limit used with the LLRVs at the FRC. Not wanting to put his concerns in writing, Bikle passed this on to Gilruth during a telephone conversation and he was disappointed that no one at the MSC considered it a problem. Later events would show that Matranga's concern was well founded.

NASA Monograph, NASA SP-2004-4535, Pg. 139, 140
As Algranti later recalled about this period at Ellington:
"__We had three different fatal T-38 accidents__, and each investigation took a significant toll on Aircraft Operations Division resources. These were followed by another three accidents, starting with Joe Engle, astronaut pilot representative on the C.C. Williams (T-38 NASA 922) accident board, who had a training helicopter accident (late in 1967)–out of gas at night!–with no injury, but which totaled the OH-13H Army chopper (NASA 931). The Center assigned Neil Armstrong to head up the Engle helicopter accident board–then he (Armstrong) had his LLRV accident on 8 May 1968. MSC Management then had Joe Aligranti head up the Armstrong LLRV accident and Aligranti had his LLTV (NASA 950) accident on 8 December 1968. Evidently, an assignment to an MSC aviation board was not good for a career resumé."

WP_1

Figure 2-3. LLRV and LLTV Flight Safety History

2.4. DFRC Altair LLTV Proposed Requirements

Altair LLTV proposed requirements were presented to LLPO at a JSC meeting August 6th. These requirements are to be refined, coordinated and developed with weighting factors to facilitate the final recommendations now scheduled for next winter. A panel of Apollo astronauts and contemporary experts should be formed now and scheduled now to meet in late 2008 to develop a consensus for the weighting factors to be used in the selection process.

2.5. Independent Study by Orbital Sciences for a Gimbaled Jet

On July 8, 2008, LLPO indicated that DFRC should work with Orbital Sciences to include the gimbaled jet into the trainer trade study. Work performed to date indicates the use of modern off-the-shelf components combined with GFE and a modern design of the gimbaled jet with a more powerful jet engine, can replicate the Apollo lunar simulation accuracy with a two-place free flight vehicle capable of simulating the Altair trajectory from 1,600 feet above the surface to landing. The cost estimate for this capability which utilizes state-of-the-art rocket (launch vehicles and spacecraft attitude controls) and jet propulsion systems is likely to be competitive with any of the other six options which are likely to survive the safety and performance minimum criteria. Improved safety and reliability compared to Apollo as well as lessons learned from the human factors that contributed to two of the three accidents will be fully incorporated into this design. The design efforts to date have resulted in a minimum risk, highly capable free flight vehicle (especially when compared to any modified VTOL) that meets all of the LLTV proposed requirements. GNC flight test validation requirements need to be developed now.

3. RECOMMENDATIONS

3.1. JSC Owner-Champion & Long Lead Times

A free flight facility owner-champion needs to be established at JSC which will knit together the GNC development support with the training requirements. This will help shape the decision on whether to have free flight for training or not. If an LLRV is justified for GNC development, it would be then available with appropriate modifications as a trainer vehicle to provide the highest quality and fidelity training possible. NASA will be wise to invest in training which is at least as good as that provided to the Apollo astronauts as a mission abort during the actual landing maneuver would be extremely costly. Altair (GNC and pilot interface) development risks reduced with early pilot in the loop free flight lunar simulation validation flights will maximize the ROI potential with the risk buy down investment. Conceivably, the ROI could pay for the entire facility and operations if phased in early – contract 2.5 to 3 years before Altair Preliminary Design Review (PDR) in 2013 – well before the Critical Design Review (CDR). This should allow for acquisition, development testing (lab, ground, and flight) and be ready for Altair GNC hardware. Ideally, procurement for some of the longest lead time hardware (e.g., vertically-mounted jet engine) should be started under NASA contract in late 2009, after a comprehensive feasibility study is completed in mid-2009. Funds from the NASA Exploration Technology Development Program (ETDP) as well as Constellation Systems (CxP) and JSC Shuttle transition should be explored to support the feasibility study and long lead buys.

3.2. Winnow the Six Candidates Down Early

Several of the proposed DFRC key requirements criteria can be agreed on now based on Apollo experience and data, desktop simulations performed to date, and examination of available facts. These include:

1. **De-coupled 5/6^{ths} g vertical component:** Simulation errors in both pitch and roll for 1/6th g simulations are orders of magnitude greater than de-coupled gimbaled jet for the Harrier, the Blackhawk, and potentially the V-22. This limitation will relegate these platforms to accurate simulation of the vertical portion of the landing trajectory (the last 100 feet or so). These platforms will not simulate the earlier portion of the trajectory which challenges the pilot to use large pitch and roll angles to move at relatively low horizontal velocities and then wait for the vehicle to move while managing quickly depleting fuel reserves.

2. **Aerodynamic force detection and cancellation:** This is a problem for all modified VTOL platforms, in that they all have their primary dependency on aero surfaces for flight control. They have substantial, hard to detect forces reacting to wind gusts, and therefore would reduce significantly the fidelity of the lunar simulation in both drag and moment compensation. In contrast, the gimbaled jet design has a low drag profile. It is not practical from cost or safety considerations to consider adding reaction control rockets to an existing aerodynamic VTOL platform. Therefore response time questions of aero surfaces and vehicle dynamic response compared to reaction control rockets remain unanswered. The Aircrane /gimbaled pod can provide some sensor simulations accepting the aerodynamic errors. However the ability of the gimbaled jet to provide early flight test results for a full gamut of Altair GNC and pilot interface questions, such as cross feed of lift and attitude control systems for fuel management strategies, is not possible with aerodynamic VTOL platforms. Uncompensated drag even in light winds cause significant changes in vehicle attitude to maintain a trajectory and will result in unacceptable negative training.

3. **Center of Gravity (cg) and Attitude Control Authority:** The LLRV established the lower limits of control authority for the Apollo LM and was designed and operated with tight controls over both the dry and wet (fuel management during flight) cg. The dry cg was measured within a one tenth of an inch accuracy, was ready for flight, controlled to a one-quarter inch sphere[7], and in flight to a one-half inch sphere, although a provision was made in the LLTV to allow the pilot to trim the roll balance in the rocket fuel system, a greater challenge with 18 rockets drawing from two supply tanks. This tight control of cg was necessary to assure adequate control authority as well as simulation fidelity. Aerodynamic VTOLs and rotorcraft will need to address this issue as well as it may apply equally to a successful lunar simulation capability.

4. **Acquisition costs for existing VTOL platforms:** This comparison to a gimbaled jet is key and the feasibility study for the gimbaled jet will provide a definitive answer as well as contribute to GNC development planning.

[7] Lead shot was added in small containers on each leg to allow for pilot weight variances.

5. **<u>Safety issues, i.e., Vortex Ring State (VRS) susceptibility:</u>** Ejection seats are critical to any free flight simulation activity for lunar landing operations. Only two candidates of the six, the VAAC Harrier, and the gimbaled jet provide ejection seat capability. The VRS problem for the rotorcraft and for tilt-rotor vehicles will require careful flight planning and tightly controlled flight operations to avoid VRS. This can be alleviated somewhat by operating in higher winds, which will most likely aggravate the simulation fidelity, which is poor to begin with for the aerodynamic VTOL platform as discussed above.

3.3. Selection Process Weighting Factors, Careful What You Buy

It would be unwise to accept a platform for training that can only simulate the vertical descent in the last 100 feet or so and be inferior in the earlier portions of the trajectory that teaches the motion cues and translation response times for re-designation of the landing target. Therefore, cost should be evaluated for those candidates that can meet the 5/6 g, pitch and roll de-coupled criteria and include acquisition, development, and operations and maintenance for both GNC and pilot interface development and training. Two vehicles plus a spare jet engine for GNC development at DFRC and three to four vehicles for training at Ellington Field plus a spare jet engine should be provided.

3.4. Get Going Early

The Physics of Lunar Landings Have Not Changed: Perform the GNC Flight Test Validation of fully integrated systems with the pilot in the loop at DFRC. Flight tests should be conducted at DFRC because DFRC offers unrestricted airspace and performs flight test as part of its core business. At Ellington Field there are airspace restrictions due to traffic at nearby Hobby Airport limiting flight test altitude to below 2,200 feet, or below 1,700 feet with safety margin. A new LLRV can conduct flight tests at safe altitudes at DFRC allowing a large Cirrus type (light aircraft ballistic recovery system) chute to safely recover the vehicle in the event of attitude control loss. This approach mitigates the failure mode for all 3 Apollo LLTV accidents.

Astronauts can join the DFRC program as the flight test program matures to provide early evaluations and feedback to the GNC design. Then block modifications can be made for LLTV deliveries, which will be operated at Ellington Field. The experience at DFRC in supporting GNC and pilot interface development and early astronaut evaluations will provide confidence for safe and effective training operations at Ellington Field. The following quote from the LLRV Monograph draws the comparison of flight test and training:

NASA Monograph, NASA SP-2004-4535[8], Page 138

> The schedules for the Apollo program were extremely complex, involving six prime contractors and more than 20,000 subcontractors and suppliers, for a total of about 400,000 people. Activities supporting the primary requirements of astronaut training were under intense scrutiny as a result of both general curiosity and congressional budget concerns. Research and training are different, of course. Research of the sort conducted at the FRC with the LLRV is exploratory, involving unexpected outcomes, and scheduling is of secondary importance. Astronaut training of the prime and backup crews

[8] http://www.history.nasa.gov/alsj/LLRV_Monograph.pdf

for Apollo, on the other hand, involved tight scheduling and a rigorous set of often-repeatable procedures with expected outcomes. Consequently, the expectations and capabilities for facilities, equipment, and personnel were very different at the MSC than they had been at the FRC.

4. CONSTELLATION/ALTAIR and APOLLO

The training risks for lunar landings in Apollo were summarized in the NASA MSC Minutes of Meeting of Flight Readiness Review Board, Lunar Landing Training Vehicle, Houston, Texas, 12 January 1970, three months before launch of Apollo 13 on11 April, 1970. A summary of these minutes is given in the **NASA Monograph, NASA SP-2004-4535[9], Page 151:**

(Neil Armstrong Quote)
"I felt like I was flying something I was used to, and it was doing the things that it ought to be doing."

Returning to the question of whether it was a good idea to continue using the LLTV ("buying this insurance policy," as he called it) in training commanders for future Apollo landings on the moon, Armstrong continued: "What we all have to ask ourselves is, do we want to keep buying this insurance policy? We've paid a lot of money to buy this insurance policy to improve our ability to do the landing job, and...a couple of times, we've had to pay excess premiums. And now we are at the point where we say maybe, at this point in time, we don't need to buy the policy at all. Discontinue the premiums on it and avoid the possibility of these excess premiums that might burden us in the future with another crash or something like that. My own conclusion is that we still can't afford not to insure against…. a catastrophe of one sort or another on final approach at the moon, and I think we should continue to buy the policy."

"I guess I agree with you," Gilruth responded. "I can see why it gives you the feeling of confidence because you know that you have flown something that is as close to a [lunar] landing...as anybody can devise."

"It is the only device we've had," replied Armstrong, adding that "the LLTV is the only simulation at all where you can allow the process to take place...a closed-loop process where you infer the velocities from attitude, velocities over the ground, and the actual vertical velocities coming into the picture at the appropriate velocity. I'm talking of 50 feet per second over the ground, which is the transition phase, that phase...where you are essentially just watching out the window and...doing those things to come into a hover. That's the 150 feet-per-second to 10 feet-per-second region where you really have a lot of flying."

Conrad agreed, saying, "You do get yourself in situations in the LLTV that you can't get in any place else except at the moon." [10]

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[9] http://www.history.nasa.gov/alsj/LLRV_Monograph.pdf

[10] The complete Appendix D with paragraphs inadvertently omitted from the monograph can be found at http://www.lunarlanding.info/articles/appendixd.pdf

> Six Apollo flights landed on the moon, and each flight commander manually piloted the LM safely and expertly onto the lunar surface. And not one of them, to quote Armstrong again, “came close to sticking a landing pad in a crater or tipping over. That success is due, in no small measure, to the experience and confidence gained in the defining research studies and the pilot experience and training by the LLRV and the LLTV.”
>
> As research and training vehicles, the LLRV and LLTV performed the tasks they were designed for, and did so superbly. But training is always potentially hazardous, something underscored by the loss of three of the vehicles–LLRV No. 1, LLTV No. 1 and No. 3–during the MSC’s astronaut-training program at Ellington. In spite of this, after the first Apollo landing on the moon, the training program was considered essential for preparing Apollo commanders for the final mission phase of lunar landing to touchdown. By then, it was obvious that the astronauts and managers at the MSC felt the training program not only was worth the risk of another accident occurring during training but also was indispensable in helping to prevent an accident from occurring during an actual lunar landing. In retrospect, it is clear how essential the LLRV and the LLTV were to the Apollo program. It is impossible to say, considering the difficulty Armstrong encountered on the first moon landing, whether that landing would have been successful without the training he received in the LLRV and LLTV. But with a program such as Apollo, involving national commitment, there were few arguments against being on the safe side in training and research.

As the Altair project determines the appropriate degree of training for lunar landings, the application of new technologies, such as from the Autonomous Landing and Hazard Avoidance Technology (ALHAT) program, will be brought into the decision making. However, it is unlikely the new astronauts for Altair will be as prepared as those from Apollo without free flight training to provide, as Armstrong stated, “the only simulation at all where you can allow the process to take place...a closed-loop process where you infer the velocities from attitude, velocities over the ground, and the actual vertical velocities coming into the picture at the appropriate velocity.”

The risk of failure on any lunar landing has to be minimized not only through the design, development, and certification process, but with the best training available, which has been proven by Apollo to be via the gimbaled jet concept. If the gimbaled jet is replaced by an alternative training platform, it will be necessary to demonstrate both the accuracy of earth-bound lunar simulation performance as well as the safety and cost advantages of an alternate platform.

<u>Letter From George E. Mueller, Associate Administrator for Manned Space Flight, 4/1/66, to Dr. Robert R. Gilruth Director, Manned Spacecraft Center, Houston, Texas:</u>

> “Understanding the urgency of the situation, I have approved the expenditure of funds for the construction of an LLTV operating site at Ellington AFB. I elected to take this action with some apprehension since it is understood that there is a possibility of an additional site requirement at KSC. It appears that the MSC operation will not only require the

expenditure of construction of facilities funds, but will undoubtedly increase the complexity and operational cost of the total LLRV/LLTV training program.

It is requested that MSC undertake a complete review of the lunar landing training program. The review should determine the budgetary and operational impact of single and multiple site locations. Since it is vital that the question of the KSC operation be settled as soon as possible, I would appreciate a detailed report of such a review by 15 May 1966."

Attached to this letter was a document titled "LLTV Purpose", and is included below:

"If funding, lead times, and engineering development practicalities could be ignored, an attempt would be made to duplicate every phase and every significant crew task of each space flight in putting together our training program and its support equipment. But, these factors cannot be ignored, and judgments must be made as to what sort of trade-offs can be tolerated in planning the training for each flight phase. So far, it has been possible to accomplish almost all of our flight training for earth orbital missions in simulators which have no dynamic responses, or dynamic responses that differ markedly from those which will actually be encountered during space flight. At the same time, in broad capability of the astronauts to perform piloting functions in a dynamic environment has been maintained through the use of aircraft and, to some degree, centrifuges. This generalization of the dynamic aspect of space flight in our training has been possible for two reasons: (1) In many cases the piloting tasks have been rather simple and the dynamic environment created by the vehicle's response to the astronaut's control inputs has been mild; and (2) In general, piloting functions in earth orbit have not been time critical; and the astronaut has had a opportunity to adapt to his dynamic environment during space flight. For example, had the docking maneuver been difficult for Neil Armstrong, (assuming no spacecraft malfunction) he could have practiced a docking approach over a period of several hours before actually completing this maneuver. **This is not the case for the lunar landing. Here, the astronaut will not be able to recover from unusual attitudes or untenable flight conditions relative to the ground for repeated landing attempts. The astronaut's performance during the first pass determines the success or failure of the entire lunar landing operation and possibly the survival or demise of two astronauts. There will be no opportunity to adapt to the dynamics of the lunar landing with a final bit of training over the lunar surface just before touchdown.** [emphasis added]

Estimating the risk involved in attempting the lunar landing without a dynamic trainer is largely a matter of speculation. There is, in fact, no quantitative or qualitative measure of the risk involving attempting a first landing of any research vehicle without practice in a flight trainer. Except for the Wright brothers' airplane, training for the landing phase of every first-time flight of a research vehicle has included extensive practice in flying trainers. **For example, before every X-15 flight both new and experienced pilots make numerous approaches and landings in an F-104. The F-104 can be configured to have almost the same L/D ratio and approach characteristics as the X-15. Considering the unprecedented demands imposed on the astronauts in the lunar landing operation, this would not be a good time to depart from established training**

practices by foregoing realistic dynamic flight training. The LLRV and the LLTV are the dynamic or flying trainers for the lunar landing flight phase. [emphasis added]

Two other alternatives have been considered: helicopters and the Lunar Landing Research Facility at Langley. **Although both helicopters and the Lunar Landing Research Facility will be used in pre-flight training for the LLTV, they are not in themselves suitable substitutes. The stability level and flight characteristics of unmodified helicopters are drastically different from those of the LEM. Because of the dependence on aerodynamic lift and the attendant interrelation of velocity changes, attitudes, and vertical accelerations, it would be extremely difficult, if not impossible, to approach LEM flight characteristics and handling qualities by trying to convert a helicopter to an airborne simulator.** The Lunar Landing Research Facility at Langley does approximate LRM performance with acceptable fidelity, however, the limited volume of space within which it must operate restricts training to an unacceptably small part of the final lunar landing phase." [Emphasis added.]

5. APOLLO MISSION COMMANDER'S COMMENTS ON THE LLTV

5.1. Apollo 11, Neil Armstrong

See pages 4, 5, 10, and 11.

5.2. Apollo 12, Pete Conrad

See pages 4, 5, and 10.

5.3. Apollo 14, Alan Shepard[11]

Shepard, from the 1971 Technical Debrief - "The control of the vehicle, I thought, was good. Here again, of course, I did practice with the LLTV (Lunar Landing Training Vehicle), as well as the LLRV (Lunar Landing Research Vehicle), and in the LMS (Lunar Module Simulator. I felt completely comfortable and completely in control of the vehicle all the time."

5.4. Apollo 15, Dave Scott

The following excerpt is from the GO For Lunar Landing Conference Report (conference held March 4-5 2008 in Tempe, Arizona)

APPENDIX B:[12]

An LLTV-type vehicle is absolutely mandatory – not debatable.

Pitchover is the point at which the landing methodology should be evaluated and refined. Pitchover (high gate) provides the first view of the site and is critical during the next minute or so during which the major decisions are made on precisely where to land. For preparation

[11] Courtesy of the Apollo Lunar Surface Journal http://www.hq.nasa.gov/alsj and the Apollo Flight Journal http://history.nasa.gov/ap15fj/.

[12] A Memo (February 26, 2008) from David Scott, Commander Apollo 15 (Excerpts)

and training in selecting the target point, the surface imagery is most important. The first view of the site also begins the "zoning" period, which peaks somewhat later (see below). This also begins the phase during which proficiency in an LLTV-type vehicle becomes absolutely essential.

The highest probability of success for a “manned” landing on the moon is by using the proven and reliable Apollo-type manual control concepts and functions (with some semi-automatic assistance, e.g., LPD and ROD). This includes standard hand-controllers (i.e., stick [RHC] and throttle).

Lunar Surface. As we now know, the surface of the Moon is irregular in all aspects – rocks, slopes, craters, regolith, undulation, lighting, etc. – there is no clean and level surface area greater than a few feet at most (at least within the areas that might be suitable for lunar exploration). Touchdown-point selection is best made by the human eye (significant pre-flight training assistance could be achieved from VR facilities such as the CAVE at Brown). It would be very difficult for an automatic, robotic, or AI system to select the optimum (or even acceptable) touchdown point. And for landing, dust is not a significant factor (even up to a couple hundred feet, especially for a proficient LLTV pilot) – based on experience thus far, dust occurs well after the touchdown point has been selected, and when dust does occur, Apollo LM-type cockpit displays are quite adequate for an instrument landing.

The motion of a lunar lander is absolutely unique. In particular, the 3-axis horizontal and vertical velocities are strongly and instantly coupled as functions of engine thrust level and vehicle attitude (R, P, and Y). Therefore, only a free-flight LLTV-type vehicle can be used for realistic and efficient simulation. These multi-variable operations cannot be adequately simulated in a fixed-base or moving-base simulator. Further, the LLTV-type free-flight motion cannot be simulated by a helicopter or hovercraft (either of which can however simulate the landing trajectory or path).

Automatic, robotic, and/or AI landing capabilities appear to have quite an emphasis in the conference agenda; therefore some specific comments may be helpful.

a) Automatic (robotic, AI) capabilities are becoming quite advanced, they are challenging and they are fun to develop. But they are not necessary, or even desirable for a “manned” lunar landing -- they will introduce complex and additional failure modes during the mission as well as require the corresponding time and resources necessary for integration; test and checkout; software verification; procedures development (normal, malfunction, and emergency): C&W logic and signals; mission techniques; mission rules; simulation (such as launch abort simulations due to time criticality); training; and real-time mission support,…among other factors (e.g., the age-old problem – if a red warning light flashes, what is at fault: the system or the indicator? And during the time-critical landing phase, the delay in assistance from MCC could cost you the farm).

b) Automatic (robotic, AI) systems are best applied to two areas: (1) to relieve the human burden of repetitious, tedious, and boring activities; and (2) to allow humans to do something that could not be done without assistance from an “automatic” system (e.g., a precision landing on a runway during zero visibility conditions). Landing on the Moon is an entirely different matter –the surface of the Moon is irregular in all aspects and even with precision

VR planning and programming, it is unlikely that an automatic system will be able to "see" (interpret) the surface conditions as well as the eye. Automatic (robotic, AI) systems would be great for an unmanned landing, but they are unnecessary and even compromising for a human landing.

Simulators and training should follow closely those concepts and methods developed and proven during Apollo – fixed-base simulators for systems and procedures, and a free-flight LLTV for actual flight dynamics. The Langley LLRF and other electrical-mechanical simulators introduce an undesirable lag in response. And lunar-g simulation for flight operations is unnecessary.

~ DRS

The following excerpt is from Page 6 of the GO For Lunar Landing Conference Report (conference held March 4-5 2008 in Tempe, Arizona):

Participant Discussion

Q1: Lauri Hansen, Altair project, couple of questions for you. We've actually talked to a lot of Apollo astronauts on LLTV and simulations versus LLTV, it would probably be a long discussion for several hours. Interestingly enough, there was one, John Young, who came down clearly on the side of simulations have advanced enough, you ought to be able to do this entirely with simulations. Everybody else came down on the side of you need something with real consequences, a real vehicle of some sort, and I guess of some sort is what I would like to explore just a little bit more with you. Understand what you were saying about helicopters not cutting it in the 1960s, do you see any possibility for the constraints we have today of combining a simulation experience with an existing craft, like an Osprey, obviously Harriers although nobody's fond of the maintenance and the costs that go along with that, but any possibility that makes sense from your perspective of combining an existing craft with simulation simulating a lunar field or whatever?

A1: Gene Matranga: I am not sure about the response of the new systems that would tilt their propulsion systems in order to do that, like the Harrier or the Osprey. I am just not familiar enough with their response systems to know whether they would do that. I would be skeptical, just from what I know of them, that those things are not intended to move quickly, and in some of these things you can move quickly, we moved the LLRV or LLTV to fairly significant attitudes in a short time period. I think they would have difficulty in doing that. Just my own personal opinion, based on intuition

Comment by Dave Scott in memo dated July 3, 2008:

Gene is correct. "Aircraft" do not have the dynamic response or handling qualities of a lunar lander, and they are also subject to aerodynamic forces that would be difficult to filter or cancel – not practical for lunar landing simulations. However, helicopters are quite useful in becoming familiar with steep descents and are a valuable precursor to an LLTV type vehicle.

5.5. Apollo 16, John Young[13]

Young, from the 1972 Technical Debrief - "When we re-designated to the south, we must have had 30 degrees of (left) yaw and took it back out. At that Sun angle, we could see the rocks (through the dust) all the way to the ground and I think that was a great help. From 200 feet down, I never looked in the cockpit. It was just like flying the LLTV (Lunar Landing Training Vehicle); your reference is to the ground outside. You had another thing that nobody has ever remarked about before, and that was the shadow. I really didn't have any doubt in my mind how far above the ground we were with that shadow coming down (that is, getting closer to them as they approach the surface). I had no scale of reference to the holes; but, with the shadow out there in front of you and coming down, it really takes all of the guesswork out of it. For that kind of Sun angle, if the radar had crumped, I don't think you'd have had a bit of trouble in just going right in and landing just like a helicopter. First, we could see the thing (rocks and other surface features) all the way to the ground; second, the shadow was right there to help you with the rate of descent. When Charlie says, "you stopped and you're hovering," there wasn't any doubt in my mind that I was hovering. I could look out the window and see that we're hovering just like a helicopter. We were well into the dust - maybe 40 or 50 feet off the ground - when we were doing that."

5.6. Apollo 17, Gene Cernan[14] [15]

The following discussion is largely derived from my 1991 discussions with Gene Cernan and Jack Schmitt.

Schmitt - "As I recall, everybody was eventually supposed to go through LLTV training, but they were barely able to qualify all of the Commanders. All of us did get helicopter training as a precursor to the LLTV."

Cernan - "The reasoning behind giving only Commanders LLTV training, as best I can remember, was a combination of time, cost, and, quite frankly, safety. All the lunar module pilots wanted to fly the LLTV, strictly from a piloting point of view. When I was a lunar module pilot, I wanted to fly it. But, because we didn't have plans to land on Apollo 10, there wasn't any point in either Tom Stafford or I training in the LLTV; and, even for the actual landing missions, quite frankly, there was no need for LMP LLTV training. It would have been nice gravy to put on a chicken fried steak if the LMPs could have flown it as well as the Commanders; but, in reality, there was no need. There were two people to train for each flight anyway: the Commander and the Back-up Commander; and that pretty much took up all the time that was available. There were also some very real safety issues. We started out with four training vehicles, I believe, and we ended up with one. Joe Algranti (a NASA test pilot) ejected out of the first one. He was heading our aircraft operation before Neil ever flew the LLTV. And then two other people had to eject. So I was the last to fly the last one. It was a very unstable vehicle."

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[13] Courtesy of the Apollo Lunar Surface Journal http://www.hq.nasa.gov/alsj and the Apollo Flight Journal http://history.nasa.gov/ap15fj/.

[14] Used by permission from the Apollo Lunar Surface Journal http://www.hq.nasa.gov/alsj and the Apollo Flight Journal http://history.nasa.gov/ap15fj/.

[15] Utility of the Lunar Landing Training Vehicle Commentary Copyright © 1995 by Eric M. Jones. All rights reserved. Last revised 24 September 2007

In all, Bell Aerosystems, Buffalo, NY built five LM trainers of this type for NASA. Two were an early version called the Lunar Landing Research Vehicle (LLRV). Neil Armstrong was flying LLRV-1 on May 6, 1968 when it went out of control. He ejected safely and the vehicle crashed. A later version was called the Lunar Landing Training Vehicle (LLTV) and three were built. Two of these were lost in crashes on December 8, 1968 (LLTV-1 piloted by Algranti) and January 29, 1971 (piloted by Stuart M. Present). Both pilots ejected safely. The LLTV was a more accurate LM simulator and Gene is correct in saying that only one (NASA vehicle 952) was available for Apollo 17 training.

Cernan - "The LLTV gave us training in the critical final phases of the descent, from 500 to 700 feet on down. It had a J85 jet engine which, basically, maintained a constant thrust - based upon the weight of the vehicle - and took away 5/6th of the weight. That put you in a simulated lunar one-sixth gravity environment. You had sets of RCS thrusters, just like the lunar module, to control attitude; but, in addition, you had two other, vertically-mounted, hydrogen-peroxide-fueled 'lift' rockets that were capable of handling the extra one-sixth of the weight above the five-sixth that the J85 removed. They let you control how fast you went up or went down. To fly a descent, you'd use the lift rockets to fly yourself up to about five hundred feet. Then you'd start a forward trajectory and pick a landing point a few thousand feet down a runway. The key was to practice, and to get familiar with the dynamics of a six-degree-of-freedom machine. The more experience you got, the more you could displace yourself; or you'd give yourself errors; or, as you developed proficiency, instead of flying right straight down the runway, you could move over in the grass somewhere and put yourself in a position where errors were established before you started."

"The LLTV was inherently less stable than the LM itself; and we also had to contend with gusts of wind that could cause problems. But, LLTV training was very valuable because it really put your tail out on the line. It was not a simulator you could make a mistake in and then reset. If you made a mistake, you busted your ass, quite frankly. It also really brought home the uniqueness of the problems that you get with six degrees of freedom. By six degrees of freedom, I mean that not only could you roll, pitch, and yaw the vehicle and change your thrust direction because of the main engine, you could also use the RCS thrusters and move it laterally up, laterally down, laterally left, laterally right, laterally fore, or laterally aft. You had a combination of all those things to do when you landed a lunar module, and that is why the LLTV was so realistic. It was a great training device, one of a kind and probably never will be seen or used again. The 'flying bridge'. The ugliest thing in the world; but it was an ingenious idea and an ingenious design, and I don't know how else you could have ever put yourself in a one-sixth gravity flying environment, with rocket engines, here on Earth, and still have six degrees of freedom. Helicopters are just vertical flying machines, and they were nothing like this at all."

Also used in training and in the development of the landing systems was the Lunar Landing Research Facility - shown here with Neil standing in front of the LM mock-up. The facility consisted of a large, overhead gantry which allowed the cable-suspended LM mock-up to be moved forward and down - or up and back - in response to pilot input. The figure consists of a set of multiple exposures showing the mock-up as it comes in for a landing. A view from behind and one from the side show the vehicle approaching touchdown. Note that the 'craters' are painted on the flat tarmac. Both images are frames captured by Ken Glover from a 16mm film of a training session by either Neil or Buzz in late June 1969.

In 2002, I was reminded that the Apollo 15 Training Log shows that, on 24-25 March 1970, Jack was at Langley AFB using the LLRF. Although the Apollo 15 Prime and Back-up crews were not announced until 27 March 1970, the training log shows Jack's first Apollo 15 training session was a LM Radar Briefing on 27 October 1969. Dick Gordon, the Back-up Commander, didn't join Jack in training until 3 April 1970, following the conclusion of the Apollo 12 PAO tour.

Schmitt, from a 2002 e-mail - "As I remember, that was my only use of the LLRF at Langley and I had several runs during those two days. Originally, LMPs also were going to check out in the LLTV. Development and test delays and having the LLTV operational long enough to train CDRs, however, prevented this from happening."

"Al Shepard told me in January 1970 that I would soon be assigned to a back-up crew and that I should start stealing some simulator time. I had already been doing this for many months and just increased the level of activity to scheduling time whenever the MSC or KSC, CSM or LM simulators were available. In fact, this was the reason that I was at KSC rather than Houston right after Apollo 13 launched - the simulators were available. That meant that when the Apollo 13 explosion occurred, I immediately began to work with the KSC simulator operators to develop and test navigation and engine burn procedures we thought 13 would need as well as test those developed at MSC."

"The simulator operators at both MSC and KSC were great and spent a lot of time with me as I learned the various systems and subsystems as they were presented in the two cabins. I also scheduled a lot of time with the contractor training personnel that understood the details of the various CSM and LM systems. I worked alone until Dick Gordon, Vance Brand and I began to work as a crew, probably after Apollo 13 returned, the 12 crew was free of post-flight activities, and the Apollo 15 prime and back-up crews were assigned internally. April 1970 sounds about right as my memory is that we trained for 15 months for the July 1971 launch of Apollo 15."

Note added 13 December 2005: Journal Contributor Brian Lawrence adds that, based on unconfirmed but seemingly plausible postings to sci.space.history, "In December 1966 Deke Slayton assigned six guys to do the initial testing of the LLRV. They were the CDRs and LMPs of the early crews who might have been assigned to flights with an LM. They were Borman/Anders, Conrad/Williams, and Armstrong/Aldrin. Williams made one - possibly two - flights in February 1967 before the training was put on hold for a year. He died in an aircraft accident in October 1967. Starting in February 1968 the other five men got their chance. When Neil ejected from LLRV #1 (6 May 1968), he had made 21 flights while Pete had made 13. The other three (Borman, Anders, Aldrin) had made 18 flights between them. When flights resumed in June 1969, there was no time for any of the LMPs to fly the vehicle."