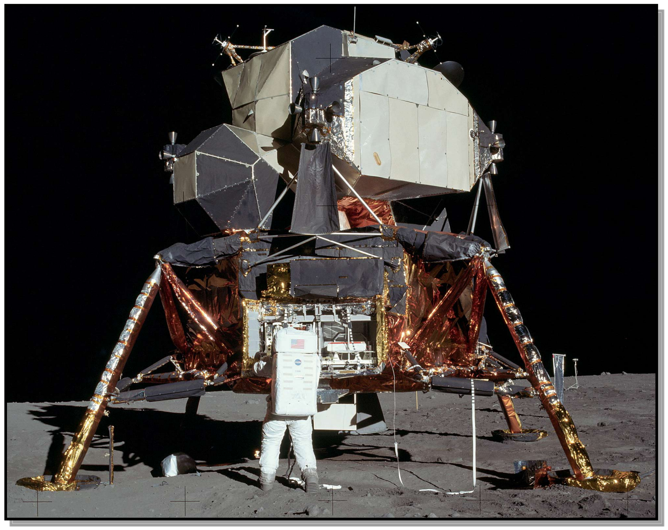
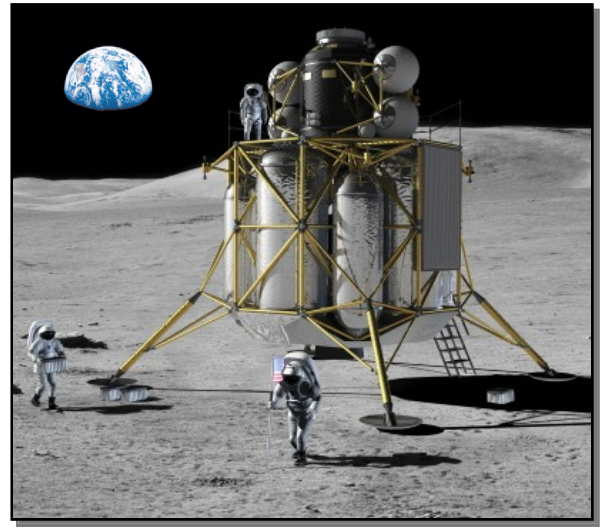
Lunar Lander Handling Qualities





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Commercial Space Seminar – Space Portal Office

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Outline

- Handling qualities background
- Motivation for spacecraft handling qualities work
- Handling qualities for precision lunar landing
  - Piloted simulations
  - Key results
- Lessons learned

Handling Qualities Background

- Handling Qualities
  - Ease and precision with which pilot can execute a flying task [Cooper & Harper]
  - Depend on vehicle dynamics, control systems, visual cues, inceptors, etc.
  - Good handling qualities give pilots a "buffer" to address off-nominal events

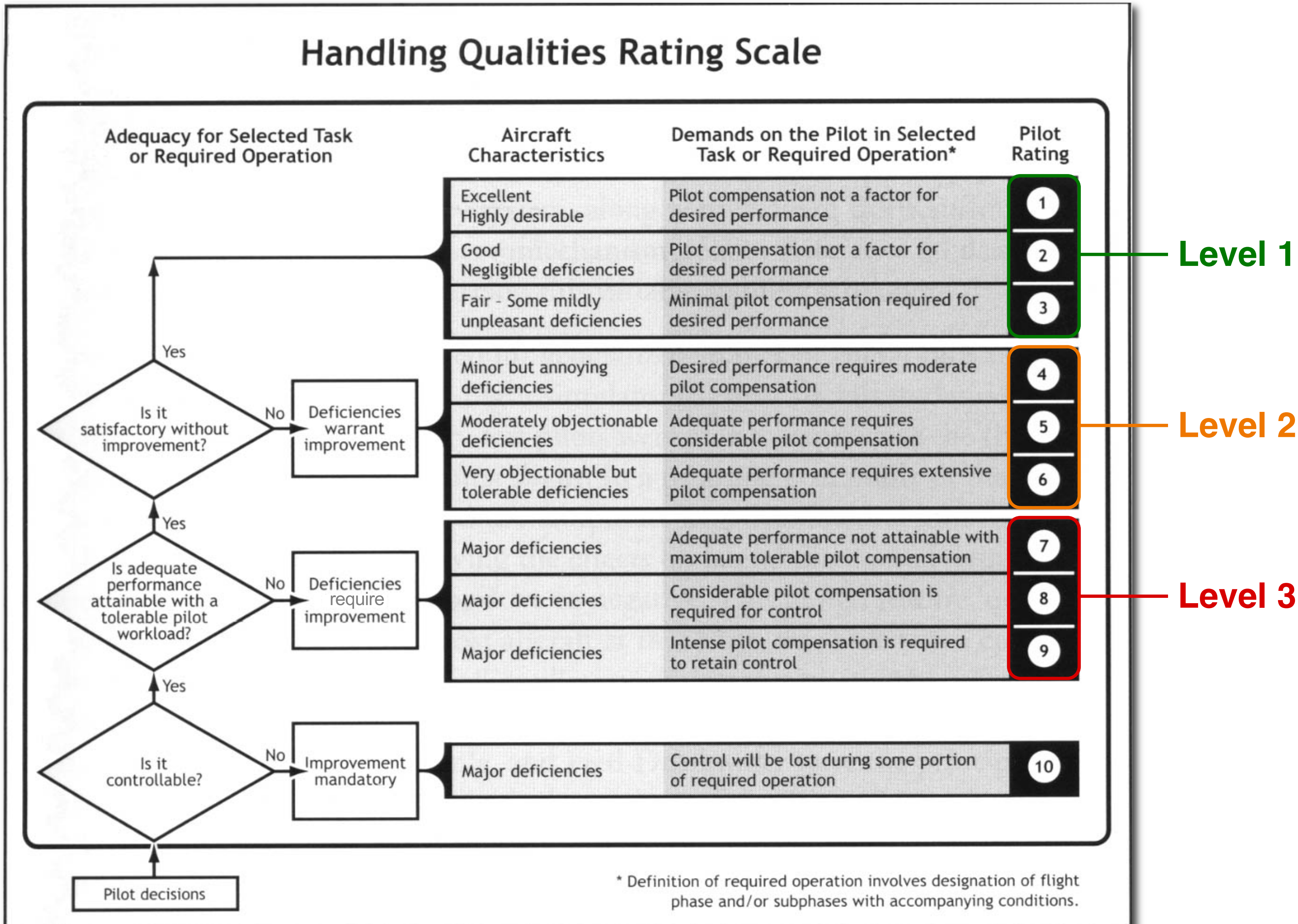
- Cooper-Harper scale is widely used for handling qualities rating
  - Pilot is briefed to fly task and achieve specified performance parameters
  - Pilot rates handling qualities based on performance and effort, along an ordinal scale of 1 (best) to 10 (worst)
    - Pilot commentary is very important
  - Handling qualities levels

Level 1 Required for normal operations

Level 2 OK for some off-nominal operations

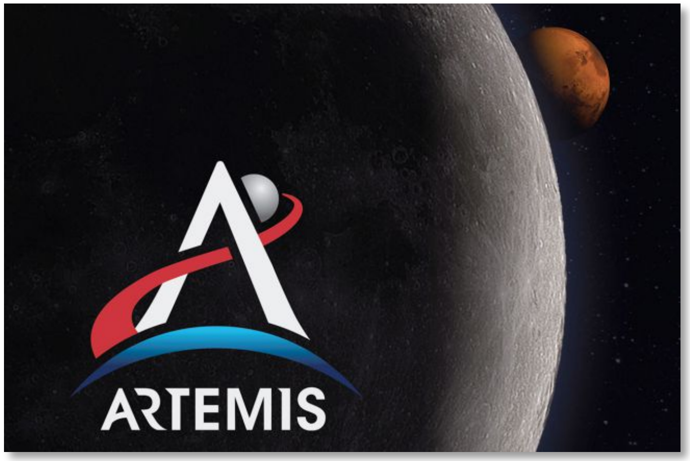
Level 3 OK only for transitioning to safe mode after major failure/disturbance

Cooper-Harper Rating Scale



Importance of Spacecraft Handling Qualities

- Spacecraft with good handling qualities can provide operational benefits by reducing training costs and mission risk
- NASA requirements for human-rated spacecraft (NPR 8705.2C)
  - Manual control of flight path and attitude
  - Satisfactory handling qualities
- There are currently no design standards for spacecraft handling qualities
- A comprehensive knowledge base would help spacecraft designers make trade-offs early in the design stage to meet handling qualities requirements

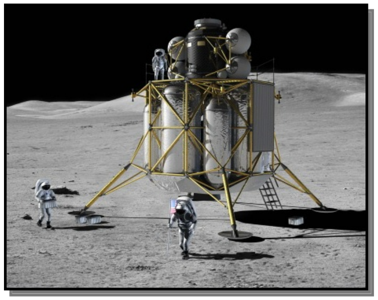


NASA Ames Studies on Spacecraft HQs

- Six studies of spacecraft handing qualities were conducted during 2007–10

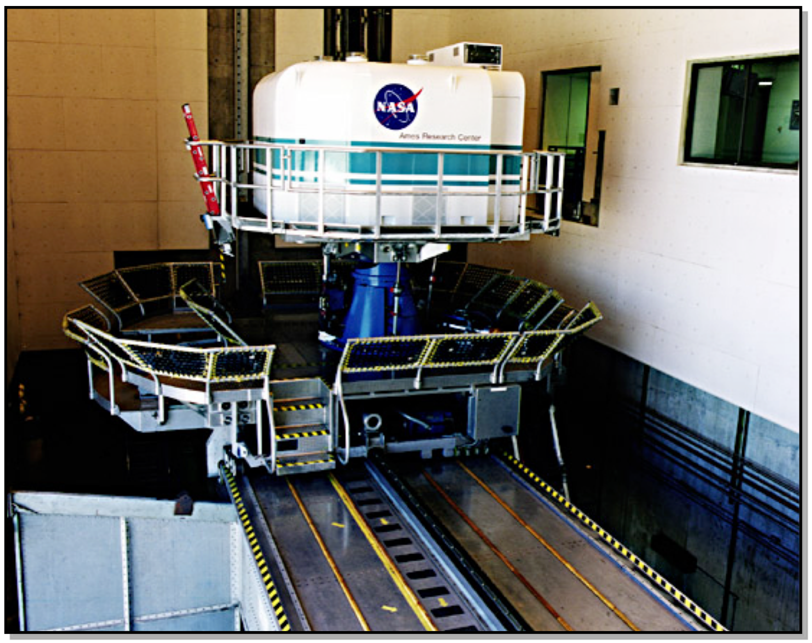
- Flying tasks studied
  - Lunar Landing
  - Proximity Operations and Docking
  - Atmospheric Entry

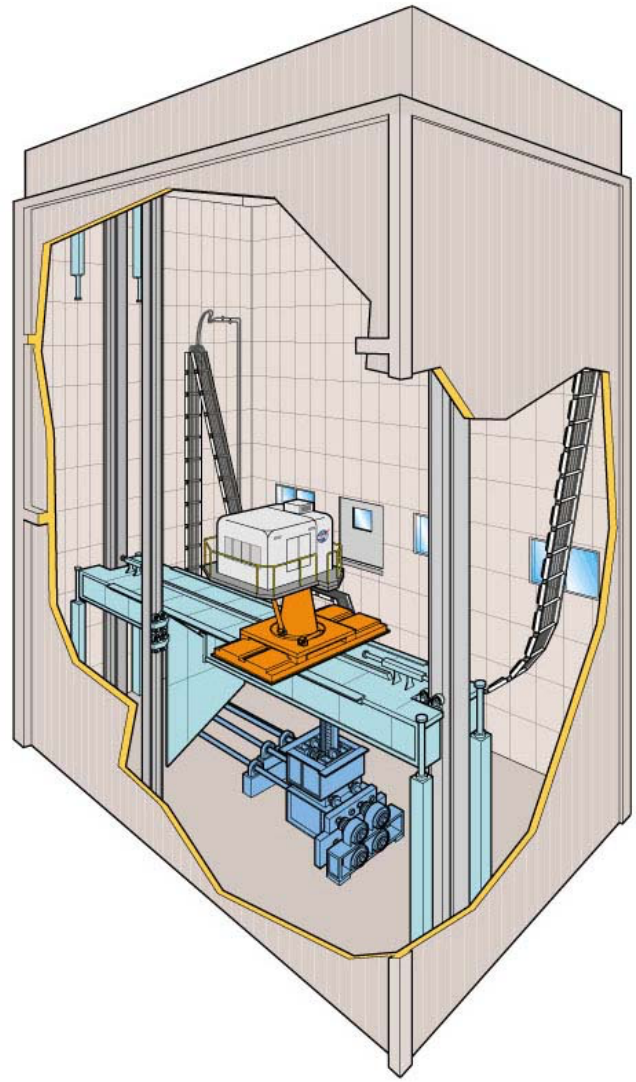
- Handling qualities evaluated by a distinguished group of pilots
  - 4 Apollo Lunar Module pilots
  - 30 Space Shuttle pilots
  - 4 NASA test pilots
  - Each study had 6 to 14 pilots, and ran for about 3 weeks



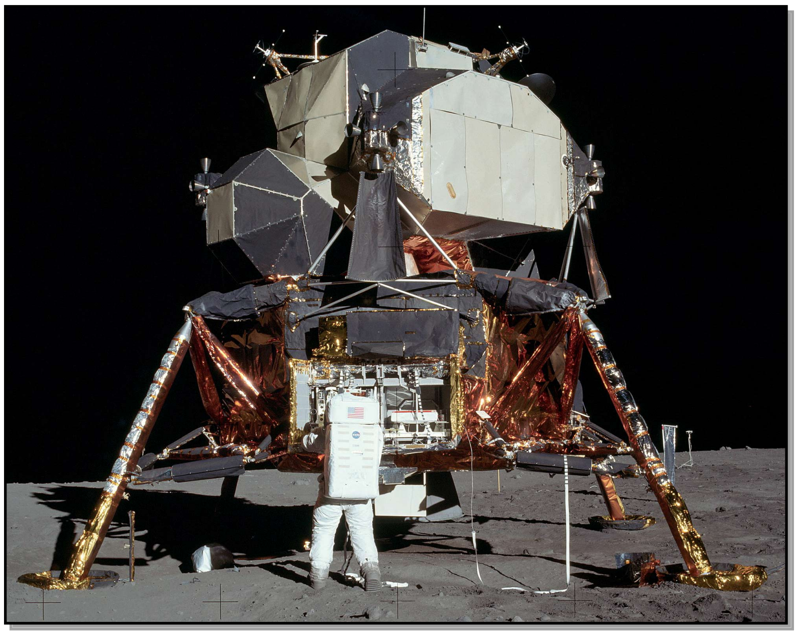
Vertical Motion Simulator

- Largest motion travel of any ground-based flight simulator
  - Vertical travel: 60 ft
  - Horizontal travel: 40 ft x 8 ft
  - Six degrees-of-freedom motion
  - Rotational and translational motion drivers are independent each other

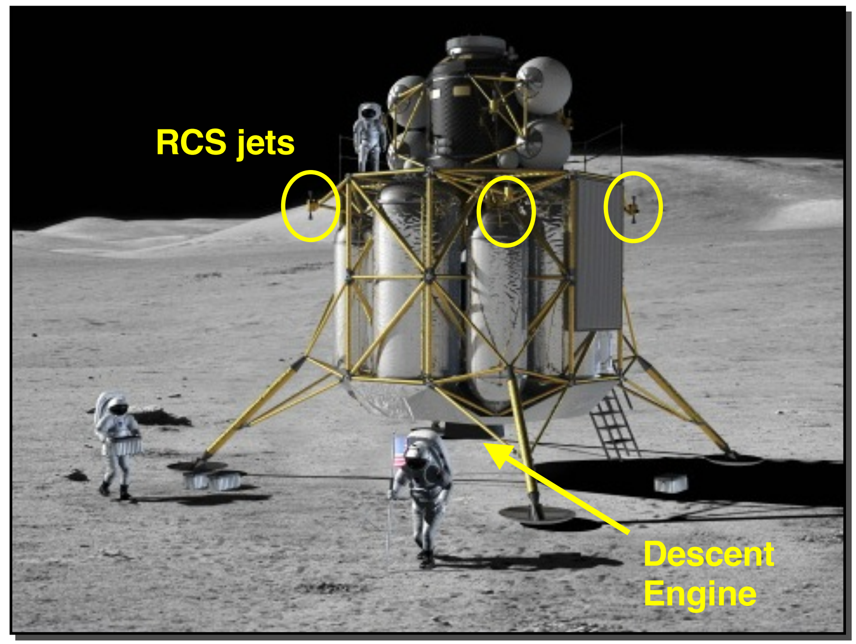




Lunar Landing Studies



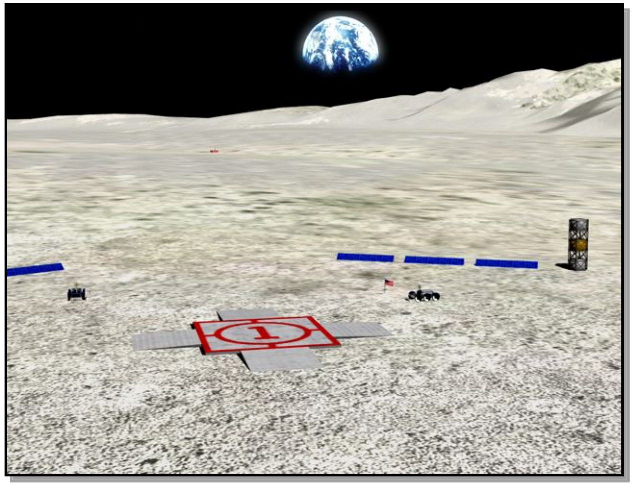
Apollo Lunar Module

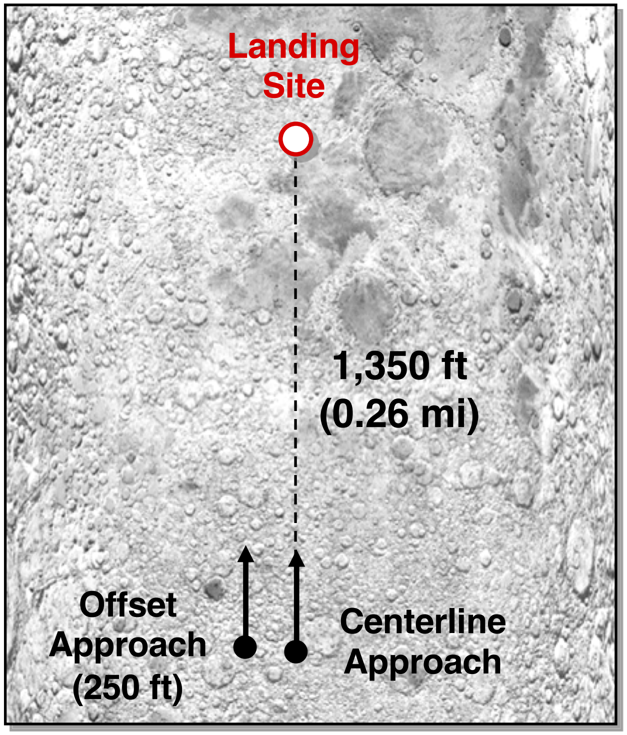


Altair Lunar Lander

Flying Task: Overview

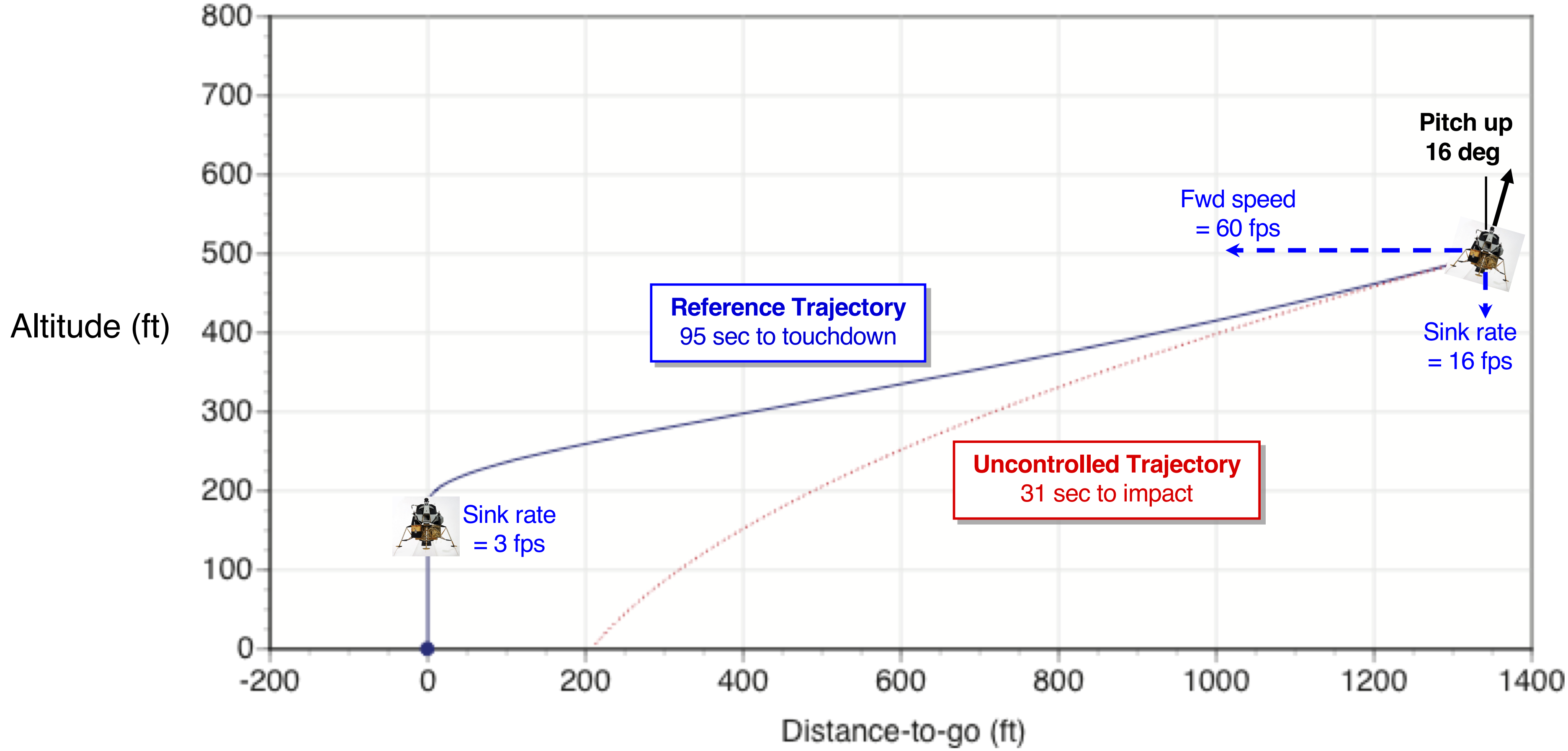
- Initial conditions
  - 1,350 ft range with 250 ft lateral offset
  - 500 ft altitude
- Pilot controls trajectory using two hand controllers
  - Rotation controller for coarse trajectory changes to arrive over landing site
  - Translation controller available for fine trajectory changes over landing site
- Requirements for precision landing
  - Touchdown position error less than 15 ft
  - Limits on attitude, angular velocity, forward speed, descent rate, propellant



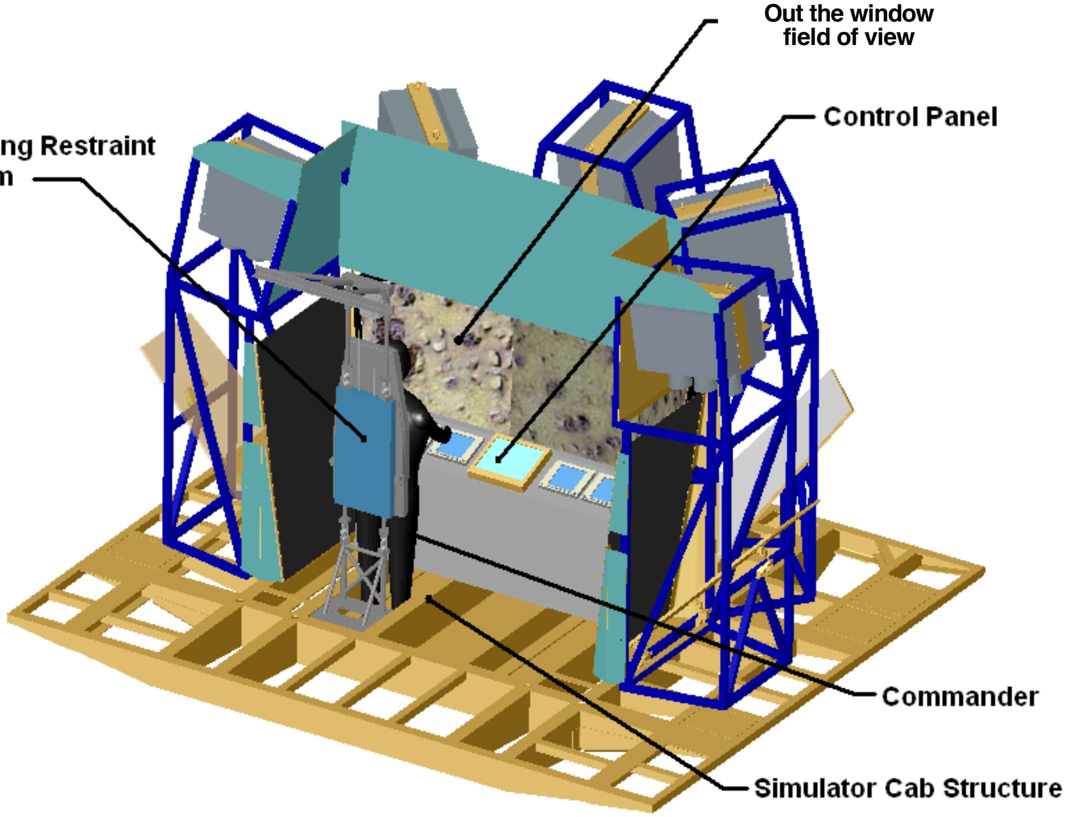


Flying Task: Vertical Profile

Vertical trajectory derived from Apollo missions
Manual control from Low Gate to touchdown

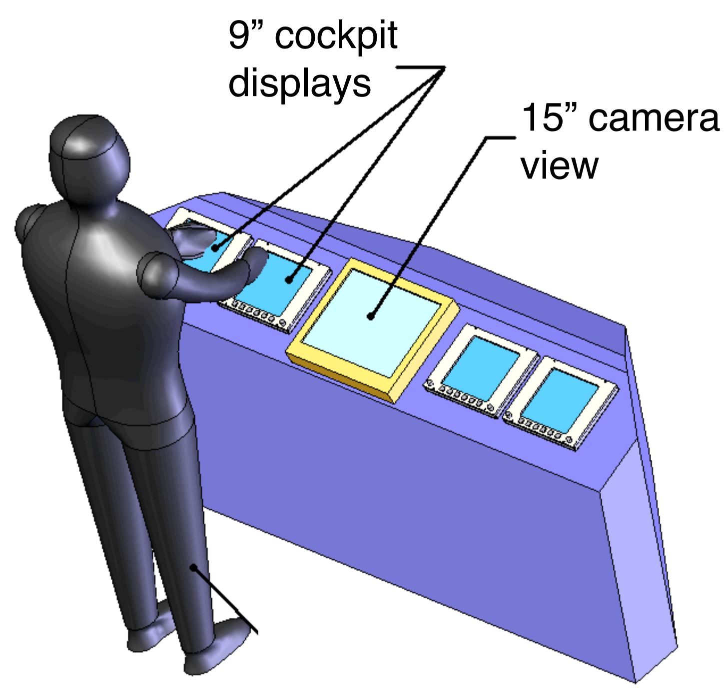


Simulator Cab Layout

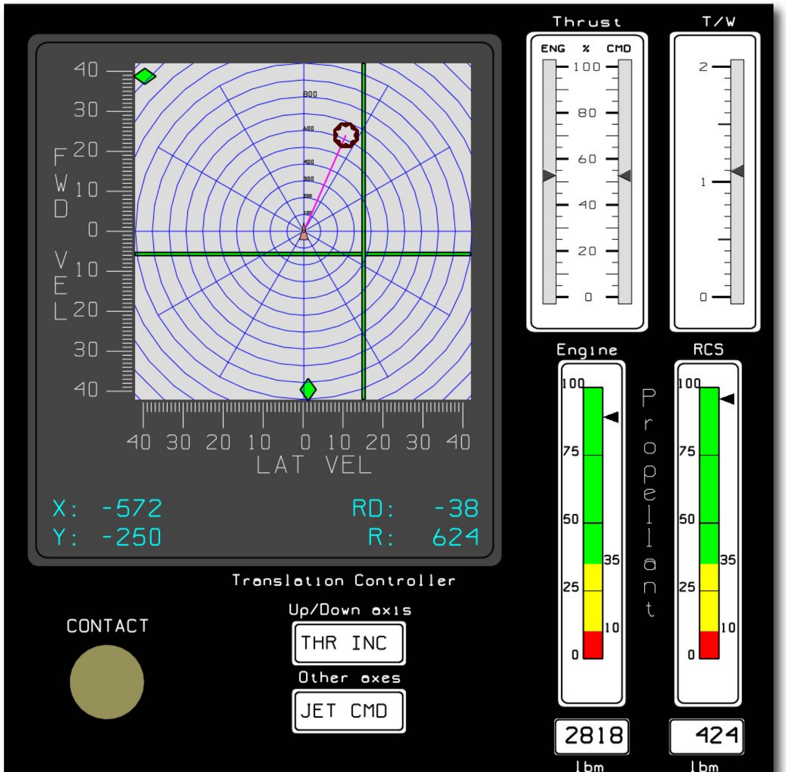


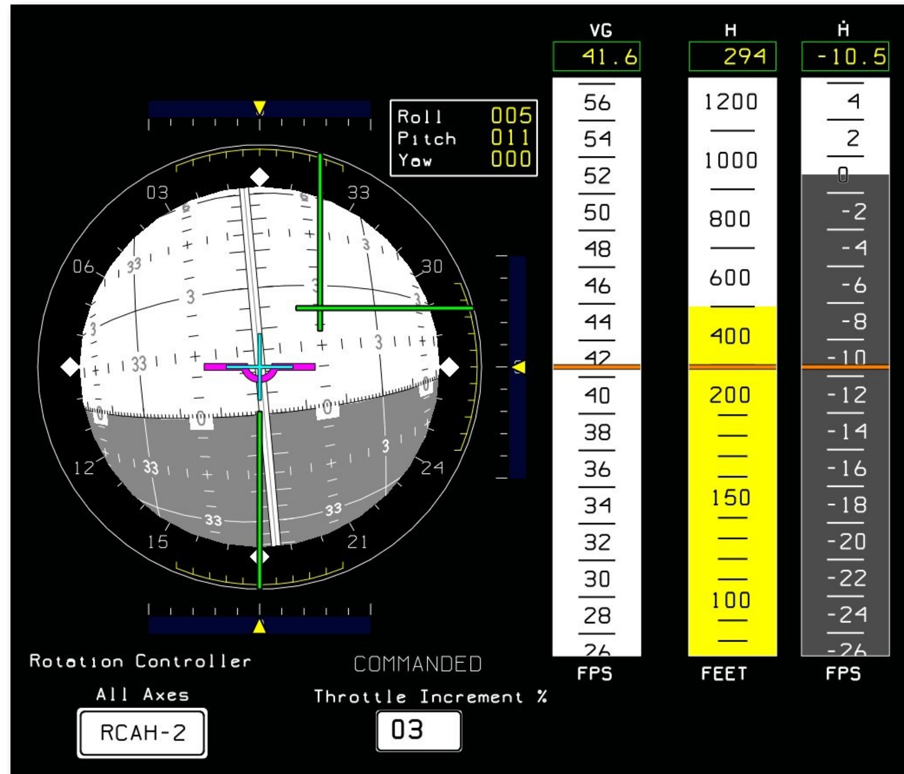
Translation
Hand Controller
(THC)

Rotation
Hand Controller
(RHC)



Basic Cockpit Displays





Objective – Lunar Landing Experiment #1

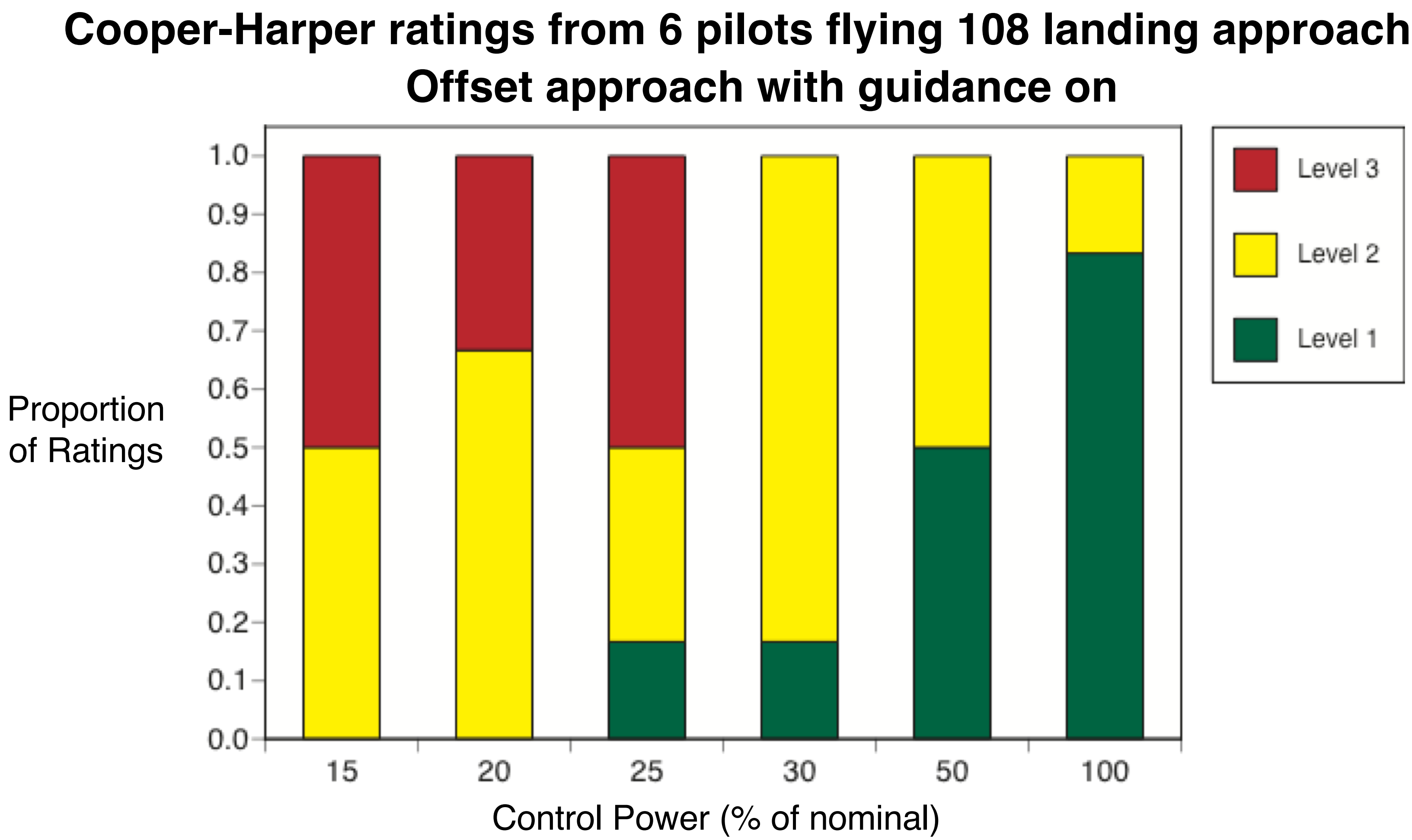
For precision lunar landing task, study effects on handling qualities due to:

- **Control power** (angular accelerations provided by control jets)
- **Guidance cues** (roll and pitch error bars)

Control Power → / **Guidance Cues ↓**	15%	20%	25%	30%	50%	100% Apollo 2-jet mode
ON (Offset Approach)						
OFF (Centerline Approach)						

For each configuration, pilots provided:
- Cooper-Harper Rating
- Workload Rating (NASA-TLX)
- Comments

Key Results – Lunar Landing Experiment #1



- Handling qualities qualities degrade as control power decreases
- Lateral offset approach very difficult to fly without guidance

Objective – Lunar Landing Experiment #2

For precision lunar landing task, study effects on handling qualities due to:

- **Control power** (angular accelerations provided by control jets)
- **Rotation command sensitivity** (angular rate at full inceptor displacement)

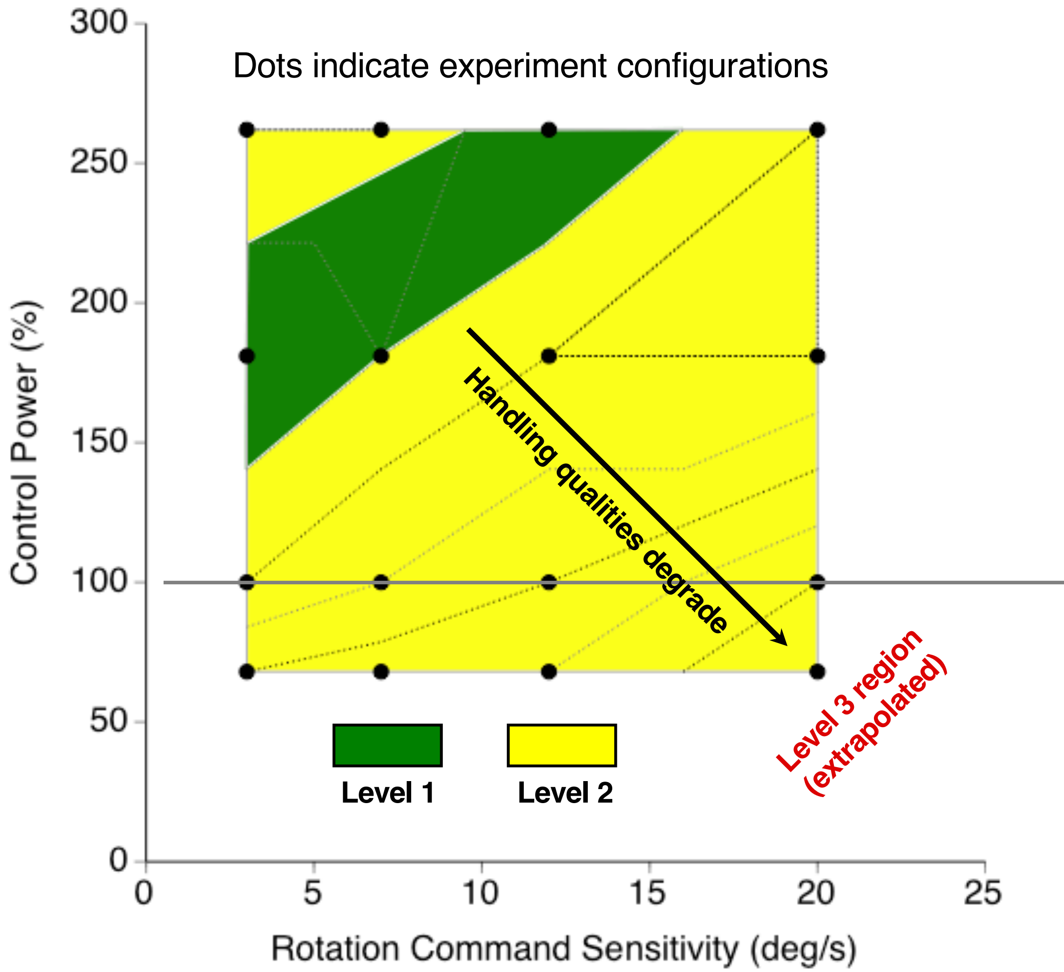
Control Power → Rotation Cmd. Sensitivity ↓	68%	100% Altair	181%	262% (~0.5 Apollo)
3 deg/sec				
7 deg/sec				
12 deg/sec				
20 deg/sec				

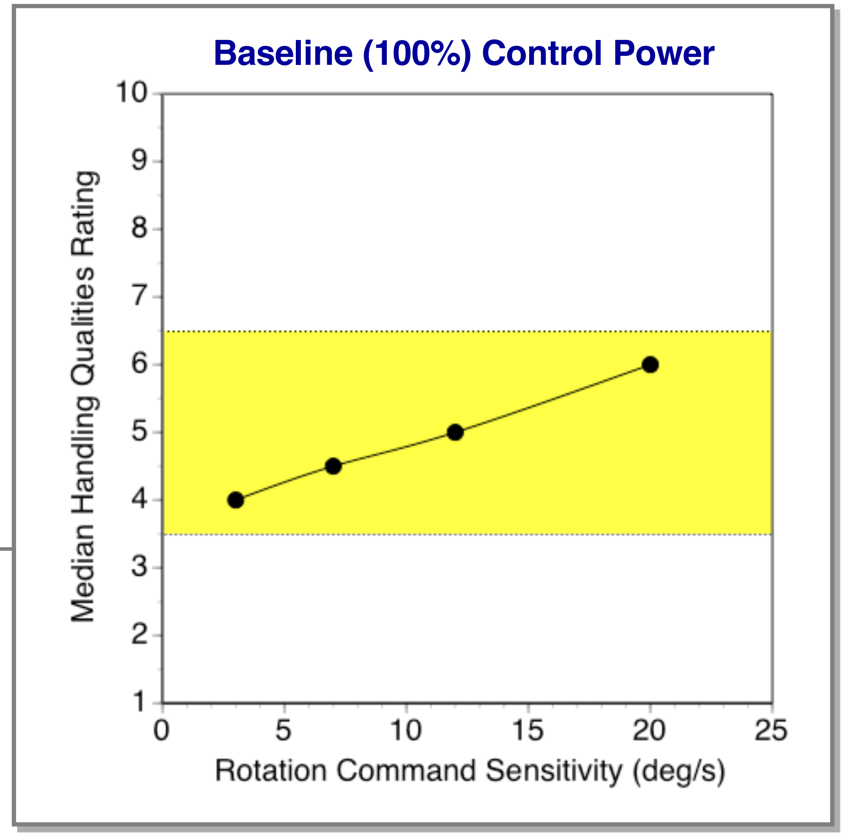
For each configuration, pilots provided:

- Cooper-Harper Rating
- Workload Rating (NASA-TLX, Bedford)
- Comments

Key Results – Lunar Landing Experiment #2

Cooper-Harper ratings from 12 pilots flying 418 landing approaches





Baseline (100%) control power configurations rated as Level 2 for precision landing

Objective – Lunar Landing Experiment #3

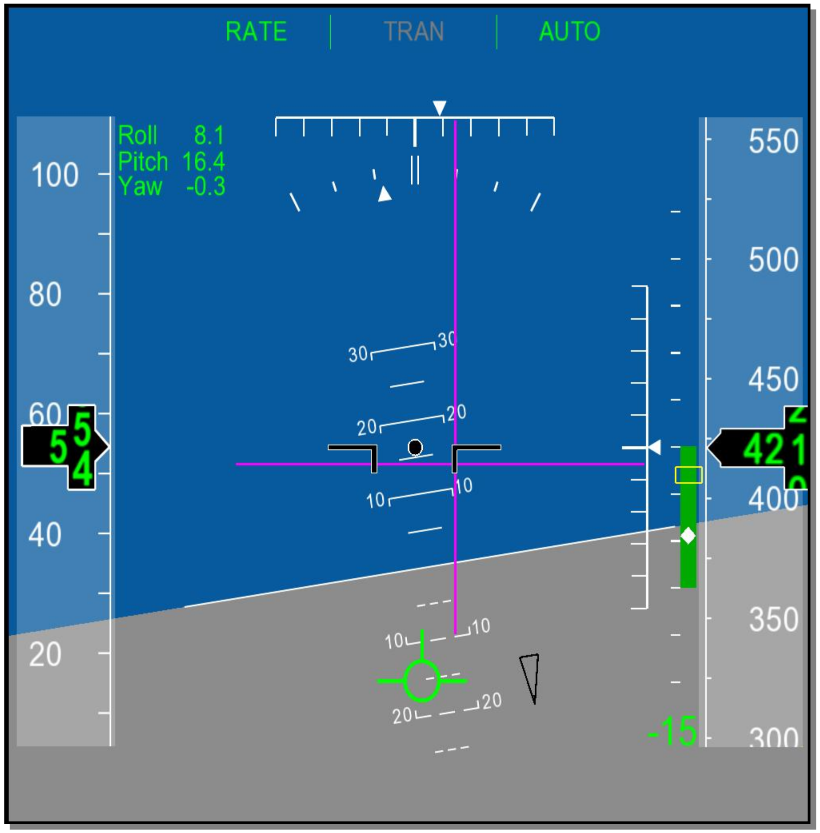
For precision lunar landing task, study effects on handling qualities due to:

- Control response types (2) tailored to up-and-away approach segment
- Control response types (5) tailored to terminal descent segment
- Cockpit displays tailored to control response types

Control response types for up-and-away segment

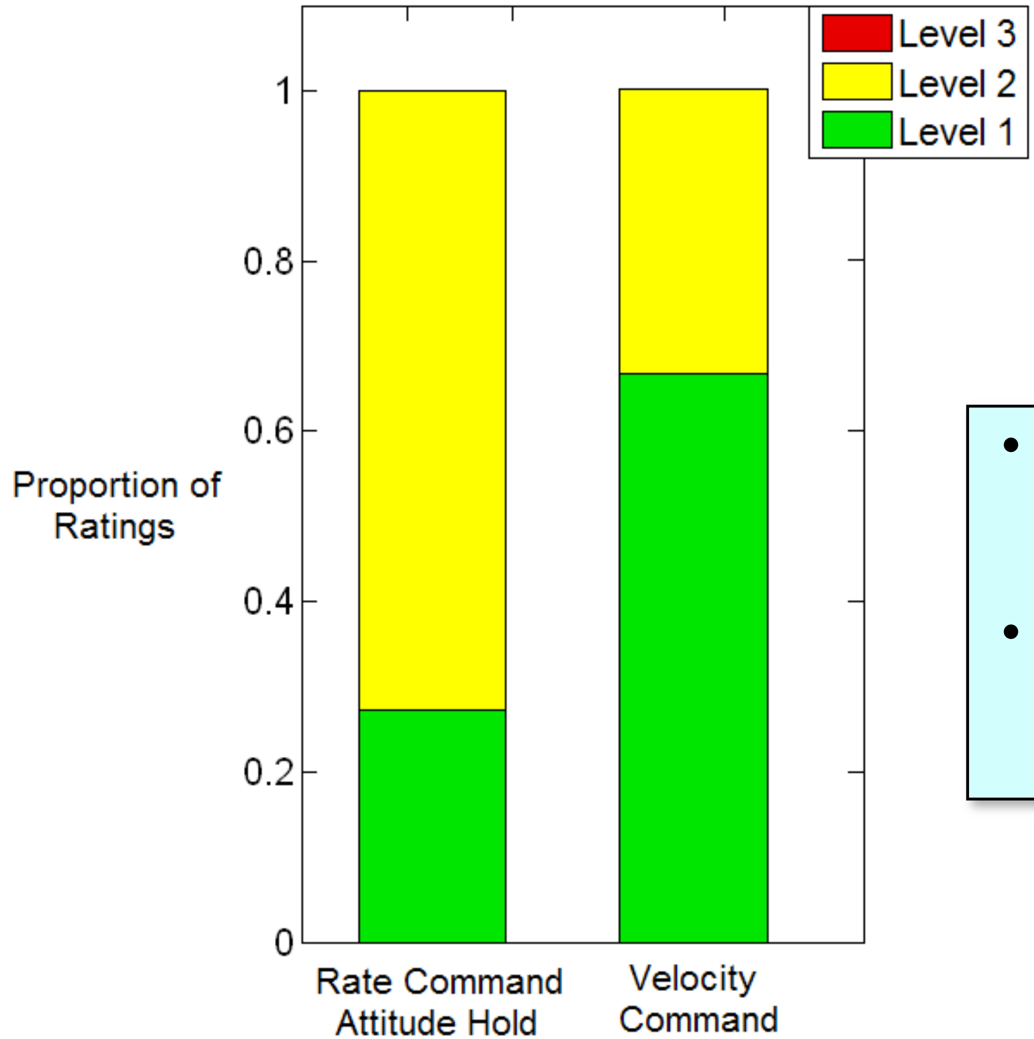
- Rate Command Attitude Hold (RCAH)
  - Basic RCAH commands attitude rate proportional to inceptor deflection, and provides attitude hold when inceptor is in detent
  - Enhanced version of RCAH was used in the Apollo LM and also in this study
- Velocity Command
  - Commands a specified velocity increment with each "click" of inceptor
  - Higher level of control response augmentation, developed for this study

Enhanced Cockpit Displays



Key Results – Lunar Landing Experiment #3

Cooper-Harper ratings from 11 pilots flying precision landing approaches



- Velocity Command control response type provides Level 1 handling qualities
- Switching to a different control mode for terminal descent segment was not preferred by the evaluation pilots

Lessons Learned

- Guidance cues are important for precision landing task
  - Lateral offset approach very difficult to fly without guidance
  - Centerline approach challenging to fly without guidance cues
- Handling qualities are affected by both control power and rotation command sensitivity
  - Level 1 handling qualities in only a small region of this design space
  - For a fixed control power, adjusting rotation command sensitivity provides a modest improvement in handling qualities at "no cost"
- Enhanced control systems and cockpit displays, tailored to the lunar landing task, can provide improved handling qualities
  - Velocity Command response type provides Level 1 handling qualities
  - Switching to a terminal descent control mode was not preferred by pilots

Some Relevant Publications

- Cooper, G.E. and Harper, R.P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

- Bailey, R.E., Jackson, E.B., Bilimoria, K.D., Mueller, E.R., Frost, C.R., and Alderete, T.S., "Cooper-Harper Experience Report for Spacecraft Handling Qualities Applications," NASA TM-2009-215767, June 2009.

- Matranga, G.J., Washington, H.P., Chenoweth, P.L., and Young, W.R., "Handling Qualities and Trajectory Requirements for Terminal Lunar Landing, as Determined from Analog Simulation," NASA TN D-1921, Aug. 1963.

- Cheatham, D. C., and Hackler, C. T., "Handling Qualities for Pilot Control of Apollo Lunar-Landing Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 3, No. 5, May 1966, pp. 632–638.

- Bilimoria, K.D., "Effects of Control Power and Guidance Cues on Lunar Lander Handling Qualities," *Journal of Spacecraft and Rockets*, Vol. 46, No. 6, November-December 2009, pp. 1261–1271.

- Mueller, E., Bilimoria, K.D., and Frost, C., "Effects of Control Power and Inceptor Sensitivity on Lunar Lander Handling Qualities," *Journal of Spacecraft and Rockets*, Vol. 48, No. 3, May-June 2011, pp. 454–466.

- Mueller, E., Bilimoria, K.D., and Frost, C., "Improved Lunar Lander Handling Qualities Through Control Response Type and Display Enhancements," *Journal of Spacecraft and Rockets*, Vol. 49, No. 2, March–April 2012, pp. 378–389.

Questions?

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