National Aeronautics and Space Administration

Handling Qualities Assessment of Manual Lunar Landing with Display Augmentation

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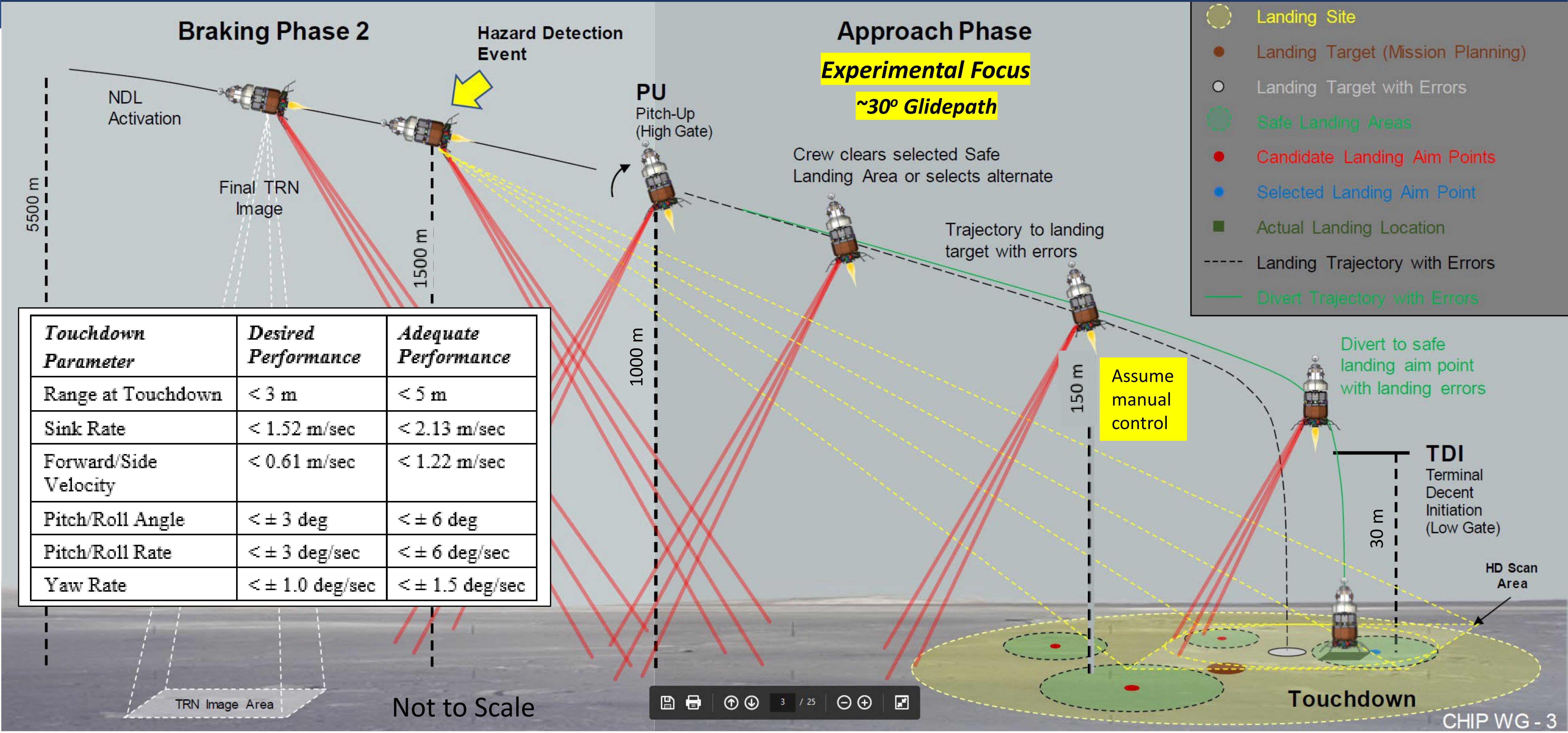
Artemis Human Landing System (HLS)

- Artemis campaign – NASA in collaboration with commercial and international partners will establish a sustainable presence on the moon to prepare for missions to Mars
- Human Landing System (HLS) spacecraft will land the first woman and first person of color on the moon
- The return of astronauts to the moon will be achieved through a combination of automatic and manual control
- A handling qualities (HQ) evaluation of control law and display concepts for manual control of a lunar landing vehicle during the final approach and landing phase was conducted
- Data from this test will support NASA and its HLS partners in manual control design insight and trade-space options for cost savings and efficiency

ConOps Overview



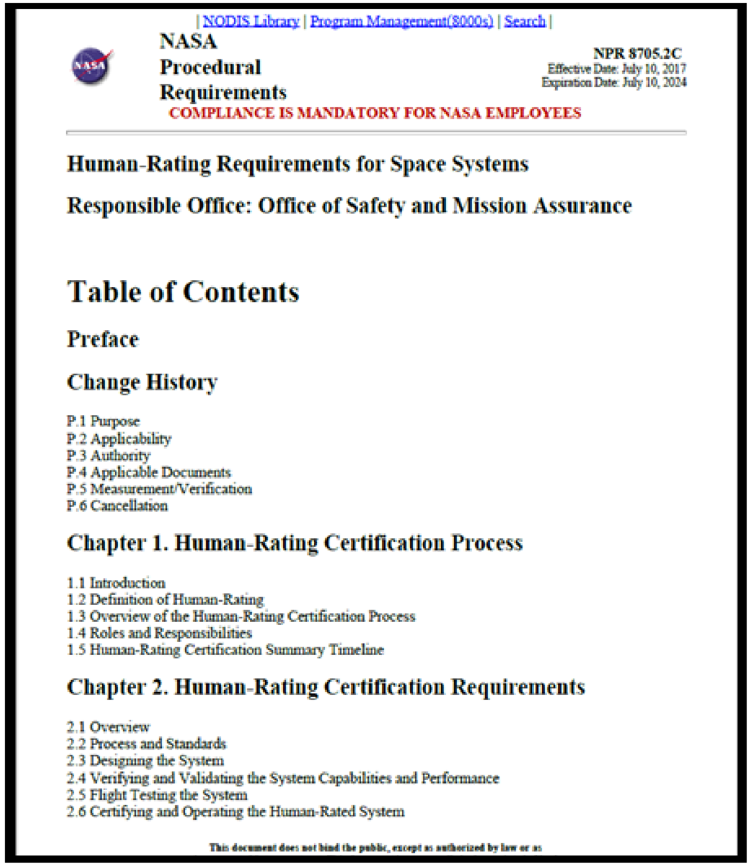
Touchdown Parameter	*Desired Performance*	*Adequate Performance*
Range at Touchdown	< 3 m	< 5 m
Sink Rate	< 1.52 m/sec	< 2.13 m/sec
Forward/Side Velocity	< 0.61 m/sec	< 1.22 m/sec
Pitch/Roll Angle	< ± 3 deg	< ± 6 deg
Pitch/Roll Rate	< ± 3 deg/sec	< ± 6 deg/sec
Yaw Rate	< ± 1.0 deg/sec	< ± 1.5 deg/sec

Background - Spacecraft Handling Qualities (SHaQ)

- A handling qualities (HQ) evaluation of control law and display concepts for manual control of a lunar landing vehicle during the final approach and landing phase was conducted
- ***Handling Qualities (HQs):***

  "Those qualities or characteristics of a vehicle (spacecraft) that govern the ease and precision with which a pilot is able to perform the tasks required in support of a *spacecraft* role."

  - Dynamics of the pilot + vehicle
  - Dependent upon the pilot-vehicle interface (control and displays); the aural, visual, and motion cues involved in the required task; any stress (e.g., distraction, time pressure) due to the task or mission; and potential external disturbances to the vehicle
- Human-Rating Requirements for Space Systems (NPR 8705.2C)
  - *3.4.2: The crewed spacecraft shall exhibit Level 1 handling qualities (Handling Qualities Rating (HQR) 1, 2 and 3), as defined by the Cooper-Harper Rating Scale, during manual control of the spacecraft's flight path and attitude for crew manual control events when the vehicle has not had failures which result in degraded fight control.*



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NASA Procedural Requirements

NPR 8705.2C
Effective Date: July 10, 2017
Expiration Date: July 10, 2024

COMPLIANCE IS MANDATORY FOR NASA EMPLOYEES

Human-Rating Requirements for Space Systems

Responsible Office: Office of Safety and Mission Assurance

Table of Contents

Preface

Change History

P.1 Purpose
P.2 Applicability
P.3 Authority
P.4 Applicable Documents
P.5 Measurement/Verification
P.6 Cancellation

Chapter 1. Human-Rating Certification Process

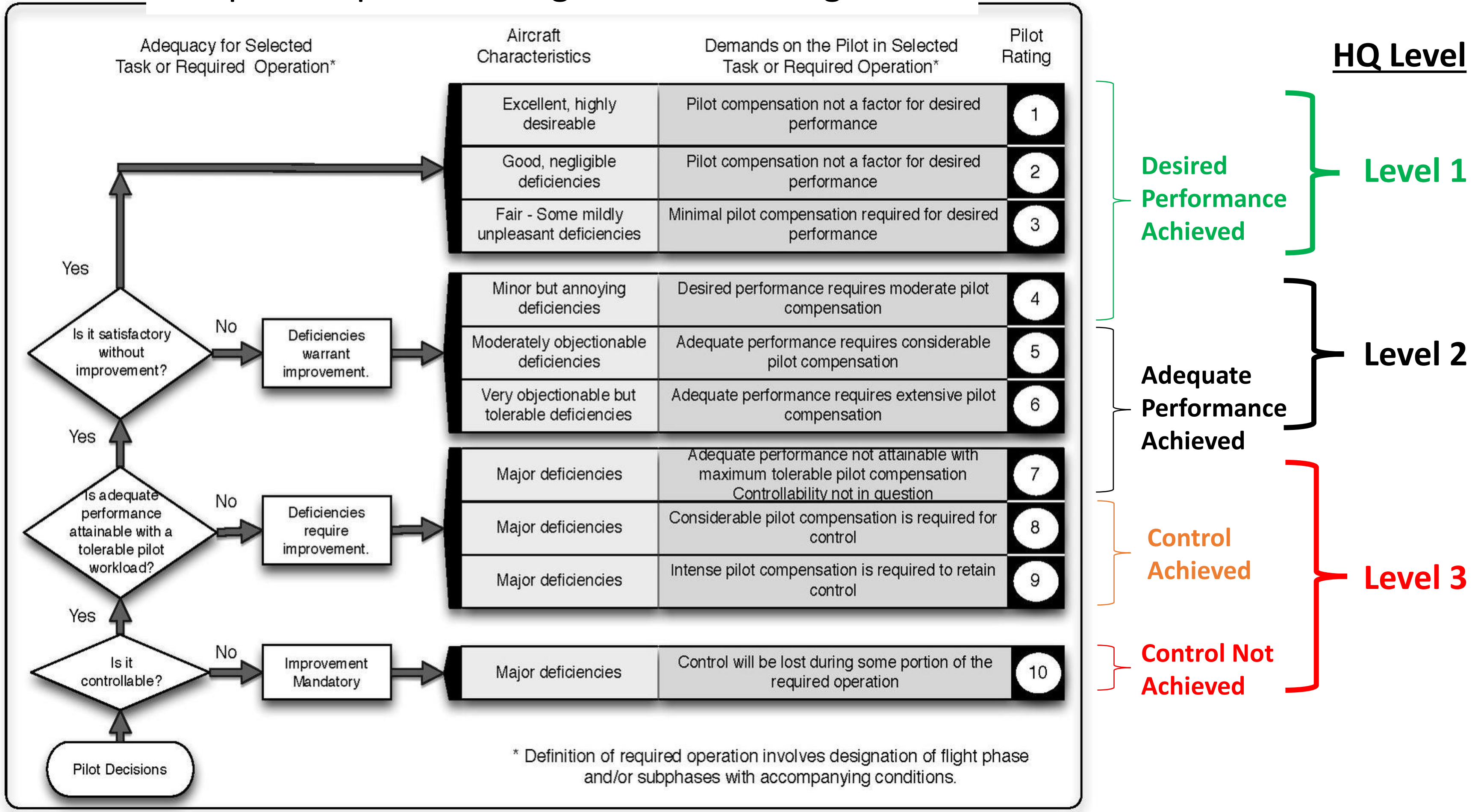
1.1 Introduction
1.2 Definition of Human-Rating
1.3 Overview of the Human-Rating Certification Process
1.4 Roles and Responsibilities
1.5 Human-Rating Certification Summary Timeline

Chapter 2. Human-Rating Certification Requirements

2.1 Overview
2.2 Process and Standards
2.3 Designing the System
2.4 Verifying and Validating the System Capabilities and Performance
2.5 Flight Testing the System
2.6 Certifying and Operating the Human-Rated System

Background - Handling Qualities Rating Scale

Cooper-Harper Handling Qualities Rating Scale



Ref: Cooper, George E.; Harper, Robert P., Jr. (April 1969). The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA- TDN-D-5153. https://ntrs.nasa.gov/citations/19690013177

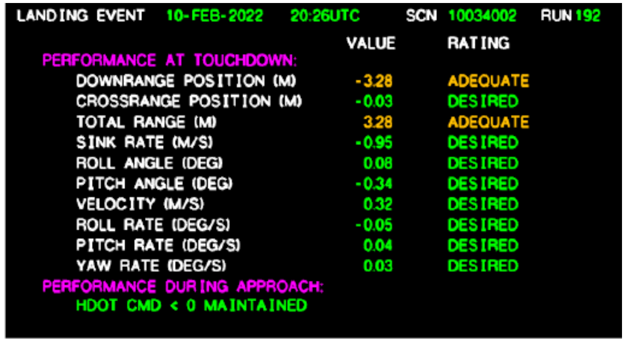
Mission Task: The pilot's task is manual control of the lunar landing vehicle for safe touchdown at a redesignated landing target using a hover cue

Desired/Adequate Performance Standards

During Approach: Maintain sink rate (i.e., hdot less than zero), have no pilot-induced oscillations (PIOs), and have no more than minimal overshoot of the landing target for *desired task performance*.

Touchdown Parameter	*Desired Performance*	*Adequate Performance*
Range at Touchdown	< 3 m	< 5 m
Sink Rate	< 1.52 m/sec	< 2.13 m/sec
Forward/Side Velocity	< 0.61 m/sec	< 1.22 m/sec
Pitch/Roll Angle	< ± 3 deg	< ± 6 deg
Pitch/Roll Rate	< ± 3 deg/sec	< ± 6 deg/sec
Yaw Rate	< ± 1.0 deg/sec	< ± 1.5 deg/sec

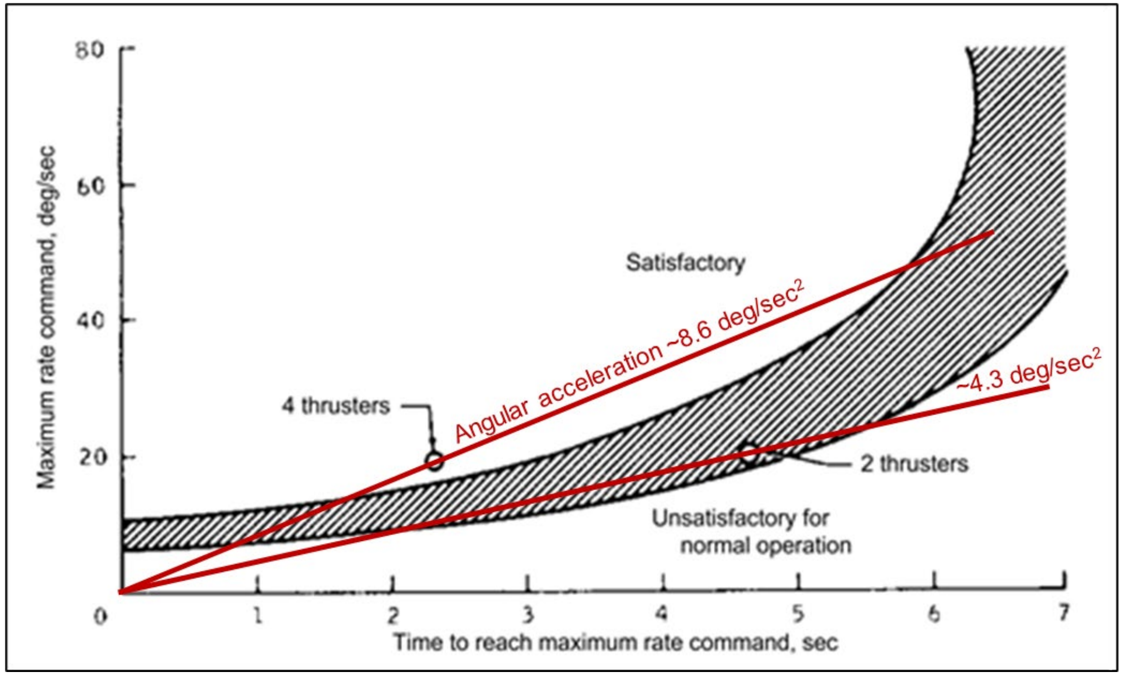
Example of After-Run Feedback of Task Performance



Existing Lunar Lander HQ Criteria/Data

- Gemini/Apollo Programs
  - HQ criteria on the required attitude control power for Satisfactory Handling Qualities
  - Max. Rate Command vs. Time to Reach Max. Rate Command
    - Used Cooper HQ Rating Scale
  - Based on Rate-Command Attitude-Hold (RCAH) control laws
    - Simple, minimum augmentation control system
- Altair Studies (Constellation Program):
  - Revalidated Apollo Criteria using Cooper-Harper HQ Rating Scale
  - Higher-level control law types appear more tolerant of lower values of control power than RCAH
    - Translational Rate Command (TRC)
    - Attitude-Command Velocity-Hold (ACVH)
  - Augmentation of RCAH with Hover Cue creates expanded Level 1 HQ area (for lower control powers)
  - Higher glideslope angle creates easier task

Cheatham & Hackler

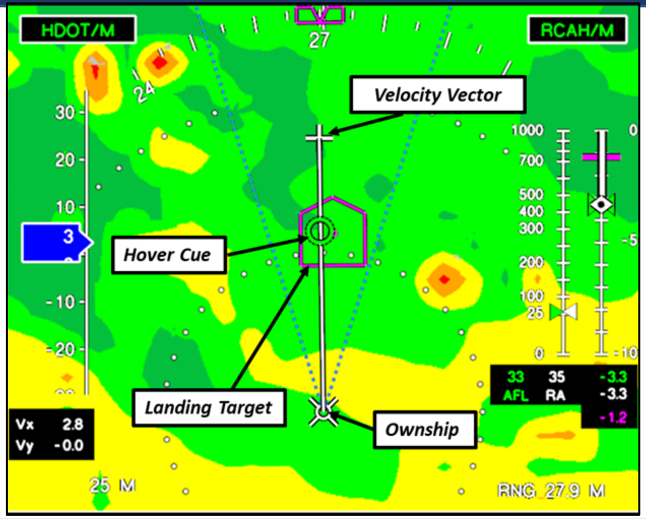


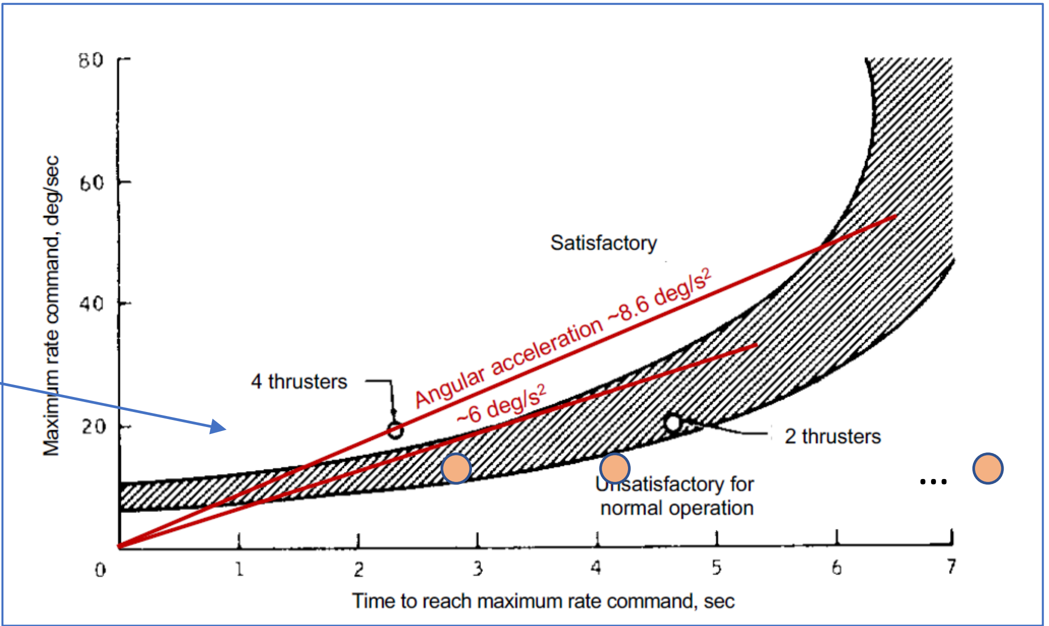
[Credit: Figure 14 from NASA TN D-4131]

Hackler, C.T., Brickel, J.R., Smith, H.E., and Cheatham, D.C., "Lunar Module Pilot Control Considerations," NASA TN D-4131, February 1968.

Current Handling Qualities Evaluation Study

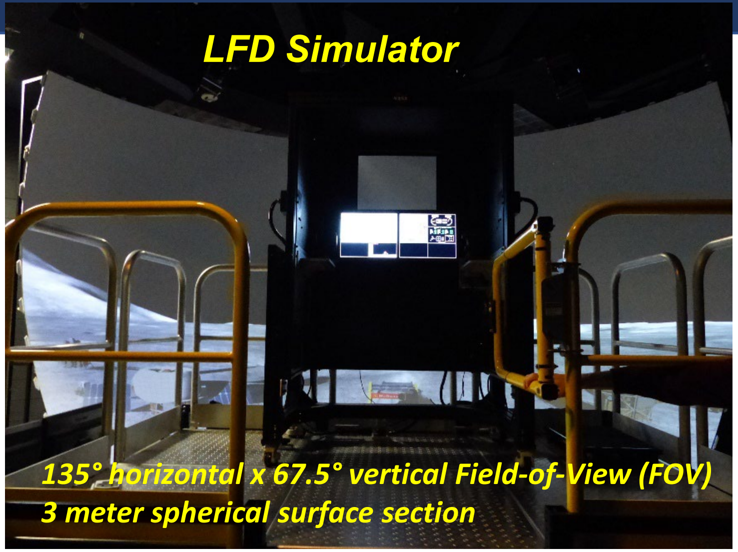
- Evaluation of control law types using hover cue on Nav Display as a display aid for precision landings
  - RCAH Control Law - 12 deg/sec Maximum Rate
  - ACVH Control Law - 20 deg Maximum Attitude
  - Both with hover cue of similar dynamics
    - Create fair comparative basis
  - Both included a Hover Hold (HH) / Incremental Position Control (IPC) mode
    - Holds vehicle position over landing target when groundspeed is less than 0.5 m/s and pilot can tweak vehicle position in 1-m increments. Provides for stabilized descent.
- Variations in vehicle characteristics are through Reaction Control System (RCS) Jet Size
  - Control powers of 1.1, 2.9, and 4.3 deg/sec^2
- Task:
  - Manual control of Lunar Landing Vehicle for safe touchdown at redesignated Landing Target (LT)

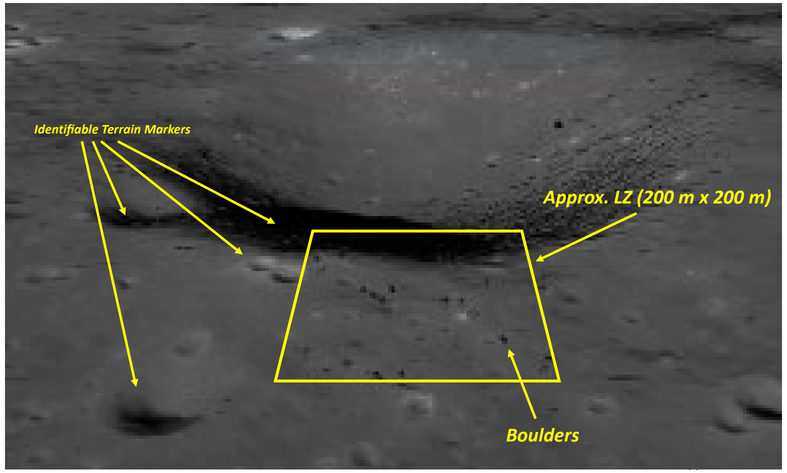


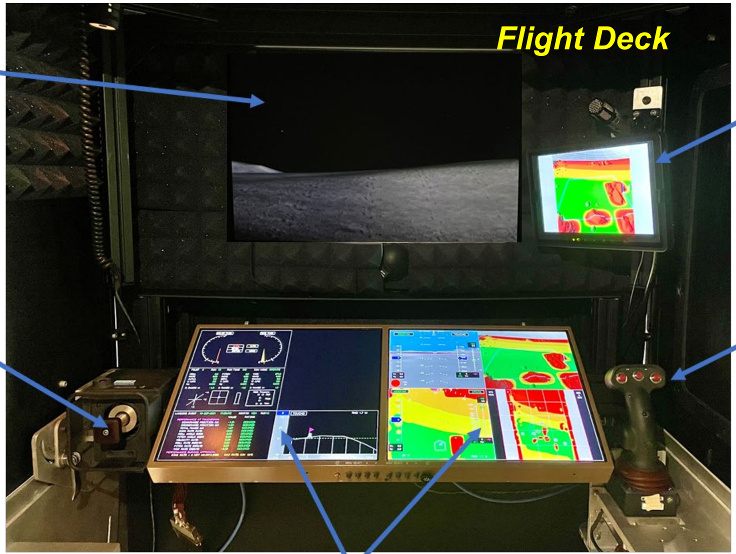


Lunar Flight Deck (LFD) Simulator at NASA LaRC

- Lunar Flight Deck (LFD) simulator
  - Flew to landing area adjacent to the Apollo 15 Landing Site
    - On a 30 deg Glidepath
    - Redesignated LT within a 200x200m Landing Zone (LZ) near Pluton crater
  - Used Altair vehicle model, LaRC Constant Deceleration Guidance
    - Allows for near constant deck angle, flight path angle and thrust-to-weight ratio
  - Used Rotational Hand Controller (RHC) for translation control with RCAH or ACVH control laws
  - Used Translational Hand Controller (THC) for sink rate (hdot) control and to move vehicle position in discrete 1-m increments in IPC mode







Piloting Task

- Task starts at 1000 m Above Field Level (AFL), i.e., Above the Landing Zone
- Flying On Auto-Pilot to 150 m AFL
- At 150 m AFL,
  - Landing Target Redesignated
    - 50 m Redez on 1st run, 2 runs to 75 m
  - Pilot gets manual control
  - Task is to translate and descend to Redesignated Landing Target
    - Arriving 20-30 m AFL, without significant overshoot
    - Then, vertical descent to landing

Desired and Adequate Performance Standards

Touchdown Parameter	*Desired Performance*	*Adequate Performance*
Range at Touchdown	< 3 m	< 5 m
Sink Rate	< 1.52 m/sec	< 2.13 m/sec
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Yaw Rate	< ± 1.0 deg/sec	< ± 1.5 deg/sec

- *No Pilot-Induced Oscillations for Desired Performance*
- *Sink Rate always maintained for Desired Performance*

Pilot Comment and Rating Card

- Quantitative Task Performance
  - Approach Path Tracking
  - Landing Performance
  - Fuel Usage
- Cooper-Harper Pilot Ratings
- NASA Task Load Index (TLX) Workload Ratings
- Post-Run Comment Card
  - Likert Ratings on acceptability of rotational control for translation and utility of cockpit displays for the task
  - Subjective Comments
- Post-test debrief

LANDING EVENT 10-FEB-2022 20:26UTC SCN 10034002 RUN 192

	VALUE	RATING
PERFORMANCE AT TOUCHDOWN:		
DOWNRANGE POSITION (M)	-3.28	ADEQUATE
CROSSRANGE POSITION (M)	-0.03	DESIRED
TOTAL RANGE (M)	3.28	ADEQUATE
SINK RATE (M/S)	-0.95	DESIRED
ROLL ANGLE (DEG)	0.08	DESIRED
PITCH ANGLE (DEG)	-0.34	DESIRED
VELOCITY (M/S)	0.32	DESIRED
ROLL RATE (DEG/S)	-0.05	DESIRED
PITCH RATE (DEG/S)	0.04	DESIRED
YAW RATE (DEG/S)	0.03	DESIRED
PERFORMANCE DURING APPROACH:		
HDOT CMD < 0 MAINTAINED		

SHaQ Pilot Comment Card – Part 1

1) Assign Cooper-Harper Pilot Ratings

2) Rotational Control

Rate Acceptability of Rotational Control for Translation to Redesignated Landing:

Totally Unacceptable	Unacceptable	Slightly Unacceptable	Neutral	Slightly Acceptable	Acceptable	Perfectly Acceptable
1	2	3	4	5	6	7

Please Comment On:

a. Rotational Control Power / Sensitivity
b. Ability to Precisely Control Translation

3) Cockpit Displays

Rate Utility of Cockpit Displays for Mission/Task:

Very Poor	Poor	Fair	Good	Very Good	Excellent
1	2	3	4	5	6

Please Comment On:

a. Hover Cue Response / Fly-ability of Cue
b. Display Influence on Ability to Complete Safe Approach and Landing
c. Use of Head-Out and Head-Down Information

4) Others:

5) Summary / Overall Comments

a. Any Change in Pilot Rating?
b. TLX Rating

Subjects and HQ Testing Protocols

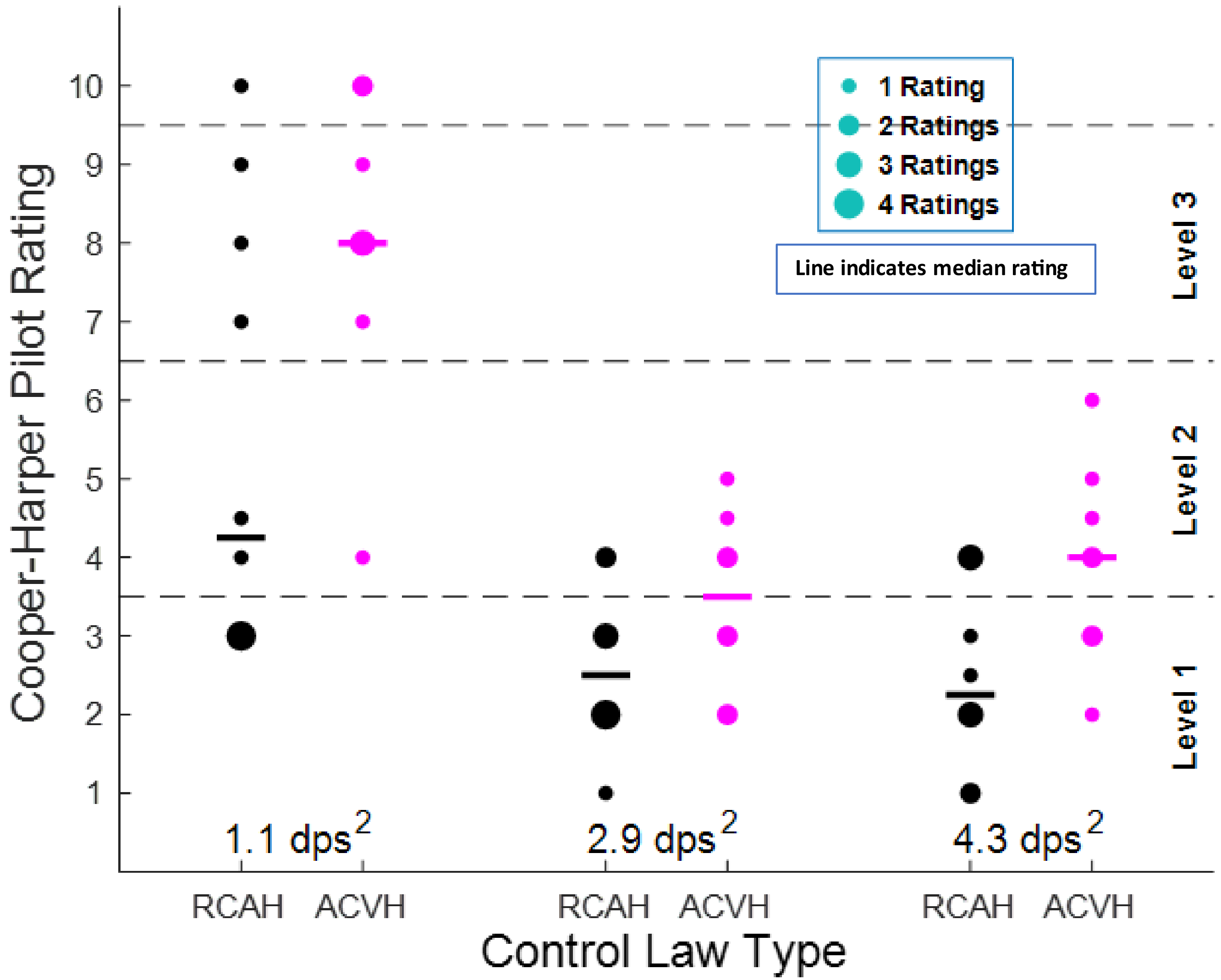
- 10 Subjects
  - 6 Current Pilot Astronauts (National and International)
  - 4 NASA Test Pilots
  - All military Test Pilot School graduates
    - Skilled in aircraft handling qualities evaluations
  - Some had experience in rotary wing vehicles
- Nominally 18 HQ runs per pilot
  - 2 control laws x 3 CPs x 3 runs
  - Blocked by Control Law, then Blocked by CP (3 runs within each)
    - Run 1: Training run with 50m redesignation distance from LT
    - Runs 2 and 3: Data runs with 75 m redesignation distance from LT
    - After data runs, pilot gave HQR rating and comments, NASA TLX workload ratings, Likert ratings

Example of SHaQ Run Card

Pilot	Config	Man Ctrl Block	CP Block (deg/sec^2)	REDEZ dist from LT (m)	REDEZ Angle from Vert (deg)
1	1	RCAH	2.9	50	-40
				75	80
				75	-75
1	2	RCAH	1.1	50	70
				75	-78
				75	55
1	3	RCAH	4.3	50	65
				75	75
				75	-38
1	4	ACVH	4.3	50	65
				75	75
				75	-38
1	5	ACVH	2.9	50	70
				75	-78
				75	55
1	6	ACVH	1.1	50	-40
				75	80
				75	-75

Cooper-Harper Pilot Ratings

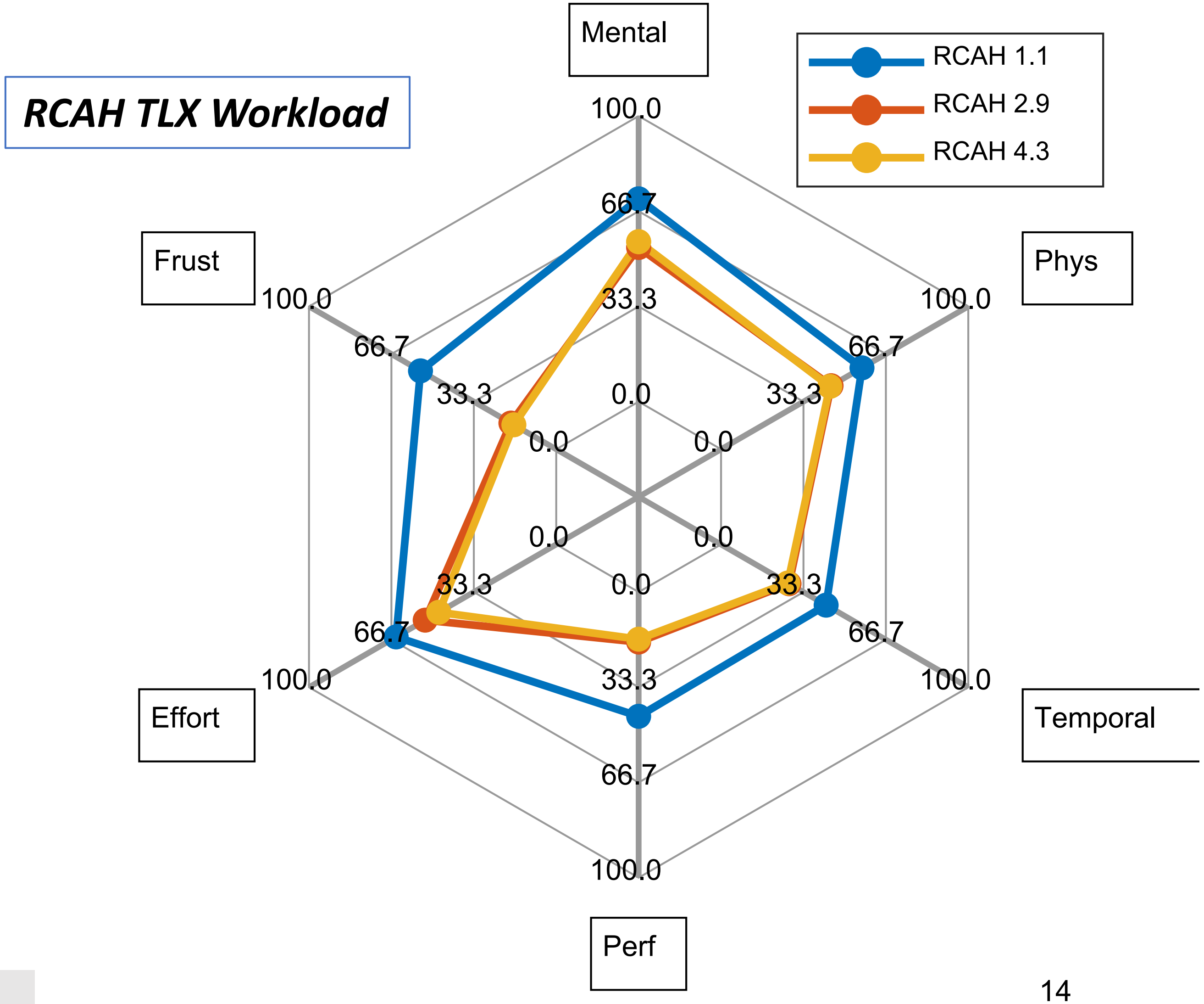
<u>Mission Task</u>: The pilot's task was manual control of the lunar landing vehicle for safe touchdown at a redesignated landing target using a hover cue.



- *Hover Cue*:
  "Changes everything."
  "I like the way the hover cue, velocity vector, and ownship position, they just play nicer together when I'm in rate command/attitude hold"
- *High Control Power*:
  "a lot more active control."
- *Low Control Power:*
  "you put in a full half stick and if you don't wait, you're gonna overshoot. And then you're sitting there holding it to stop. And then your like, "come on, when is it going to stop.""
- *RCAH v. ACVH*
  "For ACVH, in particular, is very sensitive to holding that position on the stick. If you release it, it goes [snap back] and if you put it in quick it goes [snap back] because it's taking lead from that."
- *Fuel/Redez*
  "if you add a pressure with time, fuel I think those PIOs would come out."

Pilot Workload - RCAH

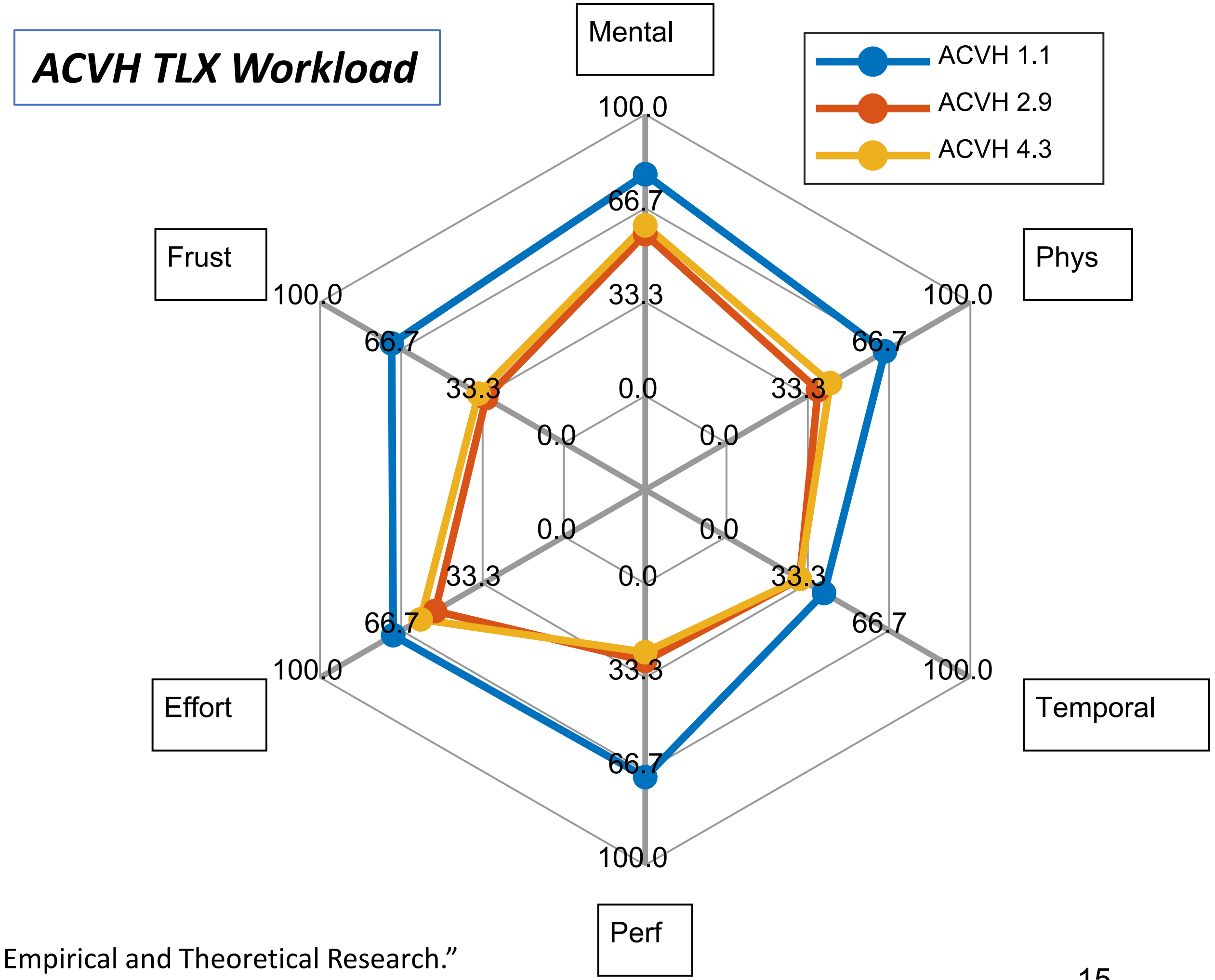
- Smaller the spider web, the better (lower workload)
  - Performance – big numbers are bad
- No significant differences between 2.9 and 4.3 deg/sec^2 control power for workload components or Overall Workload
- At 1.1 deg/sec^2:
  - Significant decrease in performance
  - Significant increase in frustration
  - Significant increase in Overall Workload



Ref: Hart, S.G. and Staveland, L.E., "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research." In P.A. Hancock & N. Meshkati (Eds.), Human Mental Workload. Amsterdam: North-Holland, 1988, pp. 139-183.

Pilot Workload - ACVH

- No significant differences between 2.9 and 4.3 deg/sec^2 control power for workload components or Overall Workload
  - Slight increase in workload for 4.3 deg/sec^2 in almost every workload attribute
- At 1.1 deg/sec^2:
  - Significant decrease in performance
  - Significant increase in frustration
  - Significant increase in Overall Workload



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Conclusions

- Hover cue display augmentation
  - Significantly improves the pilot's ability to control translation to a hover
  - Creates satisfactory handling qualities for otherwise, sluggish configurations
    - Expands acceptable (Level 1 / Level 2) envelopes for minimum control power compared to Cheatham-Hackler
    - Allows lower control power design for HLS
  - Is not a panacea as evidenced by pilot-induced oscillations and higher workload for the lowest control power
- Simpler RCAH manual control law with hover cue appears viable for lunar landing vehicles with control powers as low as 2.9 deg/sec^2
  - Test data showed RCAH was as least as good as (if not better than) ACVH when hover cue is used
  - Even lower control powers with RCAH may be viable with pilot training (using predictive, smooth control inputs; crosschecking PFD attitude), moving ND (primary display) closer to the window for easier pilot scanning, limiting landing target redesignation distance
- Hover Hold/IPC guidance mode significantly reduces workload in vertical descent and enables better "fine tuning" of the touchdown point
- Low control powers flyable as long as you don't fall over the "PIO Cliff" – dependent on attention, task upset, aggressiveness, closed-loop vs. open-loop, redesignation size, time/fuel constraint

Recommendations

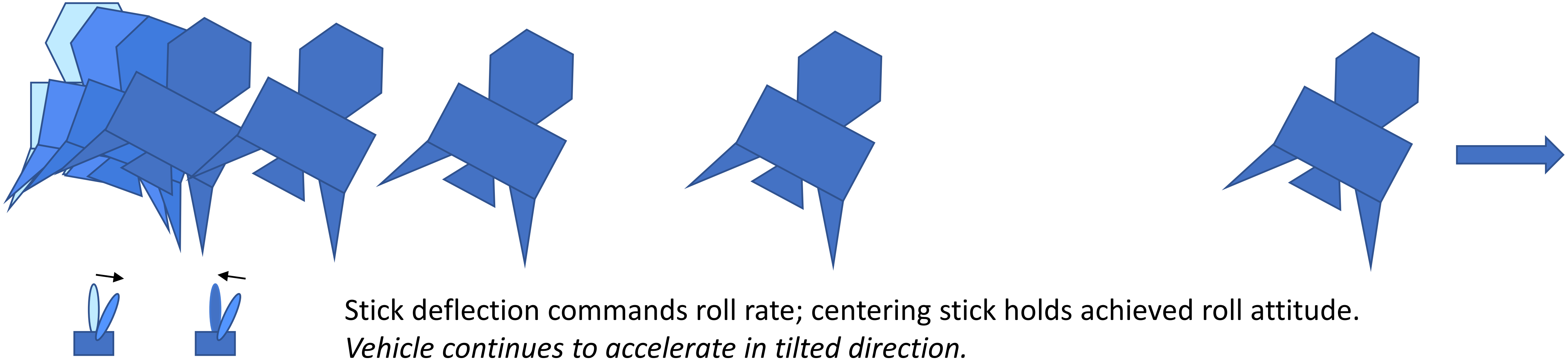
- Tailoring hover cue to configuration
- IPC as a submode of RCAH control law is recommended
- Examination of Time-Fuel Constraints / Redesignation Distance / Trajectory
  - Fuel/Time almost unconstrained for this test
- Tailoring display design/location with OTW view for improved pilot scan and attention
- ACVH (and similar control laws) need a controller without a spring-force
  - Triggered “closed-Loop” control

NASA

ARTEMIS

Flight Control Response Types - RCAH

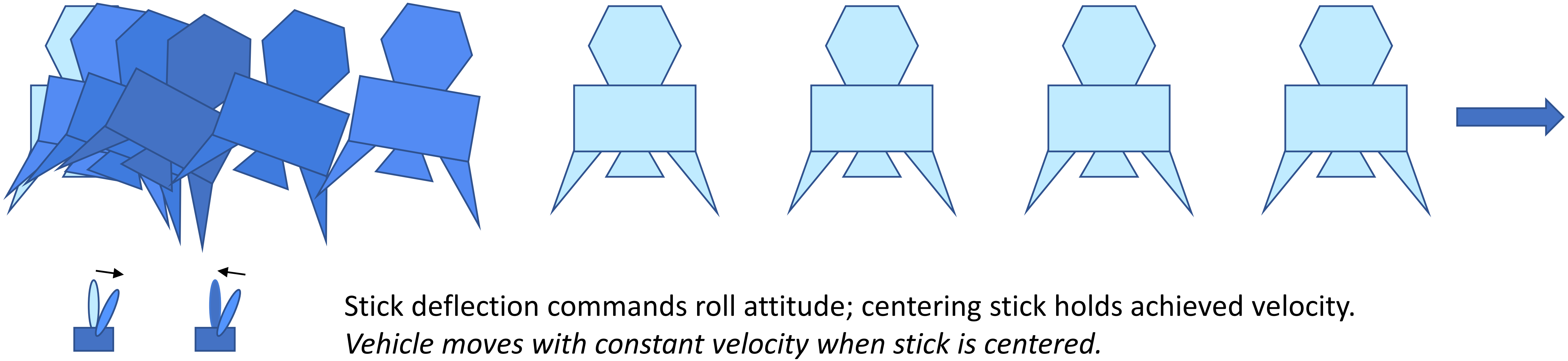
- Rate Command / Attitude Hold (Traditional Apollo):
  - Deflection of the Rotational Hand controller (RHC) will command a body angular rate in proportion to deflection in each axis (pitch, roll, yaw)
  - Upon inceptor return-to-center the attitude rates will be stopped and the new attitude will be held constant



Stick deflection commands roll rate; centering stick holds achieved roll attitude.
Vehicle continues to accelerate in tilted direction.

Flight Control Response Types - ACVH

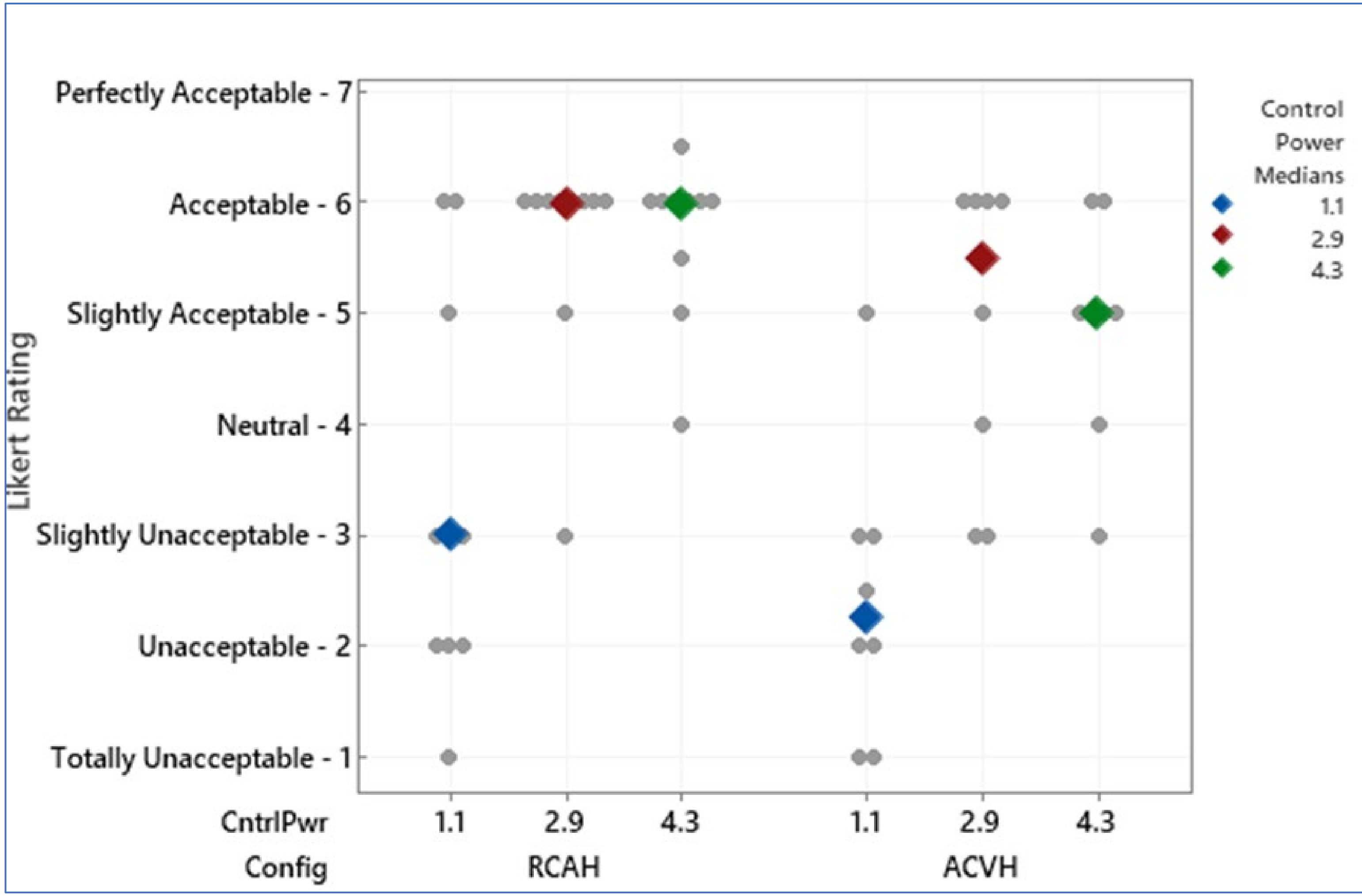
- Attitude Command / Velocity Hold (ACVH):
  - Deflection of the RHC will command a pitch or roll attitude proportional to deflection
  - Upon inceptor return-to-center the attitude will roll to level, holding current translational velocity
  - Z-axis acts as in RCAH with pilot free to yaw the vehicle as desired.



Stick deflection commands roll attitude; centering stick holds achieved velocity.
Vehicle moves with constant velocity when stick is centered.

Acceptability of Rotational Control for Translation

- Significant control power differences
  - 2.9 and 4.3 CPs had acceptable rotational control for translation
  - 1.1 CP slightly unacceptable



Example Run Matrix for Two Subjects

Pilot	Config	Man Ctrl Block	CP Block (deg/sec^2)	REDEZ dist from LT (m)	REDEZ Angle from Vert (deg)
1	1	RCAH	2.9	50	-40
				75	80
				75	-75
1	2	RCAH	1.1	50	70
				75	-78
				75	55
1	3	RCAH	4.3	50	65
				75	75
				75	-38
1	4	ACVH	4.3	50	65
				75	75
				75	-38
1	5	ACVH	2.9	50	70
				75	-78
				75	55
1	6	ACVH	1.1	50	-40
				75	80
				75	-75

Pilot	Config	Man Ctrl Block	CP Block (deg/sec^2)	REDEZ dist from LT (m)	REDEZ Angle from Vert (deg)
2	1	RCAH	4.3	50	70
				75	-78
				75	55
2	2	RCAH	1.1	50	-40
				75	80
				75	-75
2	3	RCAH	2.9	50	65
				75	75
				75	-38
2	4	ACVH	1.1	50	70
				75	-78
				75	55
2	5	ACVH	2.9	50	-40
				75	80
				75	-75
2	6	ACVH	4.3	50	65
				75	75
				75	-38

Cooper Rating Scale (1957)

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
NORMAL OPERATION	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
EMERGENCY OPERATION	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only *	Doubtful	Yes
NO OPERATION	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable - Dangerous	No	No
		9	Unacceptable - Uncontrollable	No	No
	Unprintable	10	"Motions possibly violent enough to prevent pilot escape"		

* Failure of stability augmenter

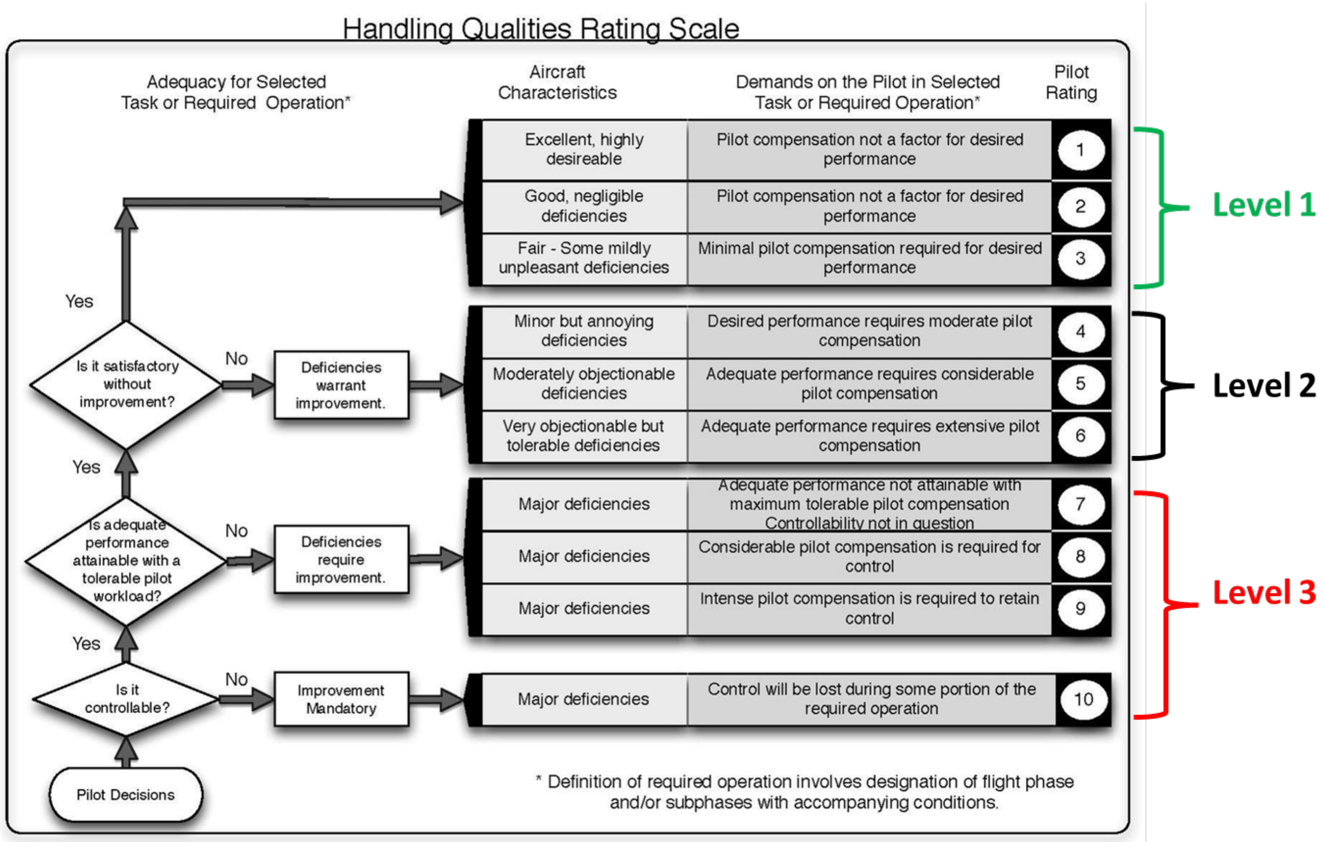
Figure 3.- Original Cooper Rating Scale.

Credit: Figure 3 from Cooper (1957)]

Reference: Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aeron. Eng. Rev., vol. 16, no.3, Mar. 1957, pp. 47-51, 56.

Cooper-Harper Rating (CHR) Scale

- Internationally accepted standard for assessing HQ for over 40 years
- Cooper-Harper scale yields a rating of pilot compensation (effort required) to achieve a specific level of performance in the accomplishment of a mission or task
- Pilots are briefed on the task to be evaluated and its performance requirements (Desired/Adequate)
- Assess performance for composite of 2 data runs (optional 3rd data run)
- Pilots should always go through the flow logic of the Cooper-Harper chart and verbalize their decision on if control was achieved, and if so, was desired or adequate performance attained.
  - Classify overall performance as desired (CHR 1-4), adequate (CHR 5-7), or inadequate (CHR 8-10)
  - ***Level 1 Handling Qualities are CHR of 1, 2, or 3***
- This rating along with the associated pilot comments and quantitative task performance data define the vehicle's handling qualities



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CHR Scale Descriptions

DEFINITIONS FROM TN-D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE

The function or purpose that defines the primary use of an aircraft.

TASK

The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

WORKLOAD

The integrated physical and mental effort required to perform a specified piloting task.

Cooper-Harper Ref. NASA TND-5153

Ref: Cooper, George E.; Harper, Robert P., Jr. (April 1969). The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA- TDN-D-5153. https://ntrs.nasa.gov/citations/19690013177

Workload: Task Load Index (TLX) rating card

Rating Scale Definitions

Title	Descriptions
MENTAL DEMAND	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Verbalize your rating for each scale:

MENTAL DEMAND

0 50 100

Low High

PHYSICAL DEMAND

0 50 100

Low High

TEMPORAL DEMAND

0 50 100

Low High

PERFORMANCE

0 50 100

Good Poor

EFFORT

0 50 100

Low High

FRUSTRATION

0 50 100

Low High

Integrated Hover Cue Symbology set

- **Composed of ownship symbol, hover cue, velocity vector, and landing target (LT)**

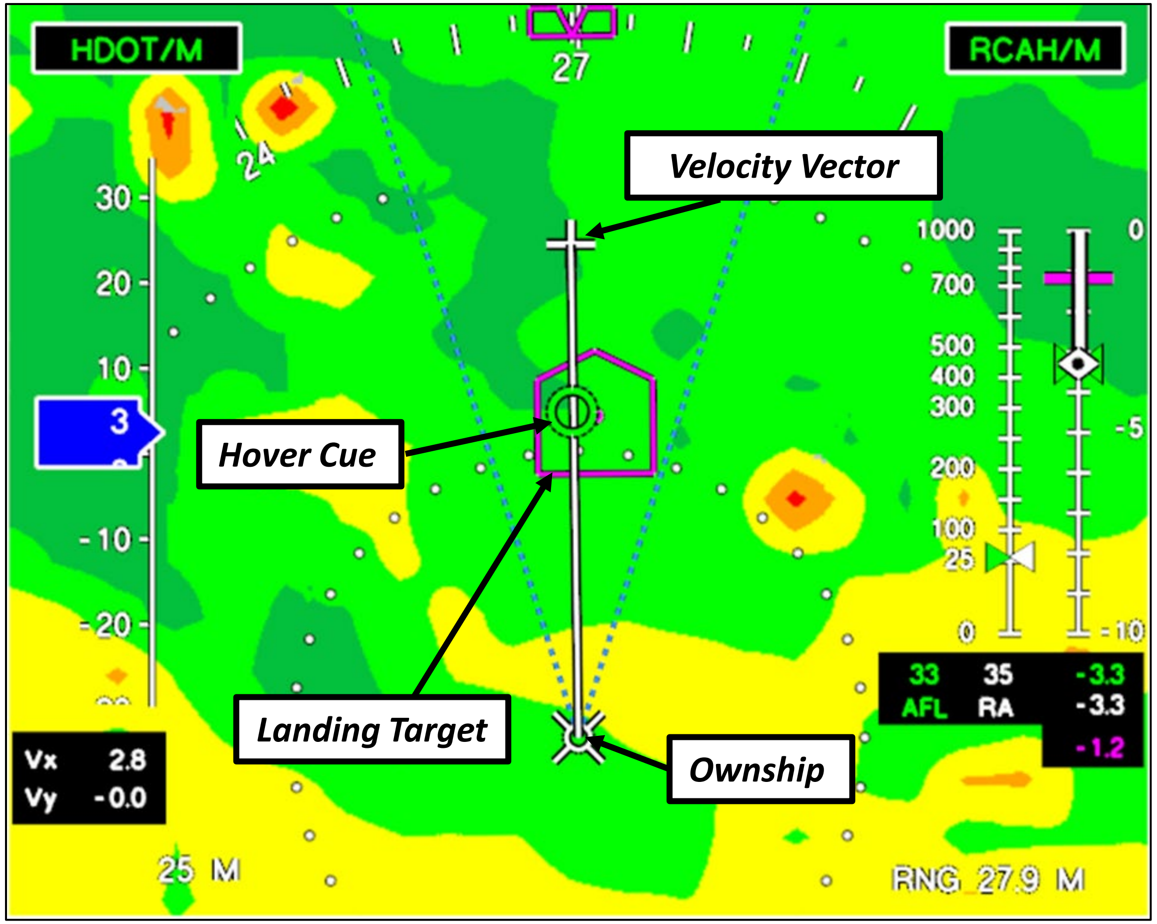
  Hover Cue → Control Symbol ("Fly-To" Sense)
  Velocity Vector → Reference Information
  Landing Target (LT)→ Desired Hover Location

Pilot's Task

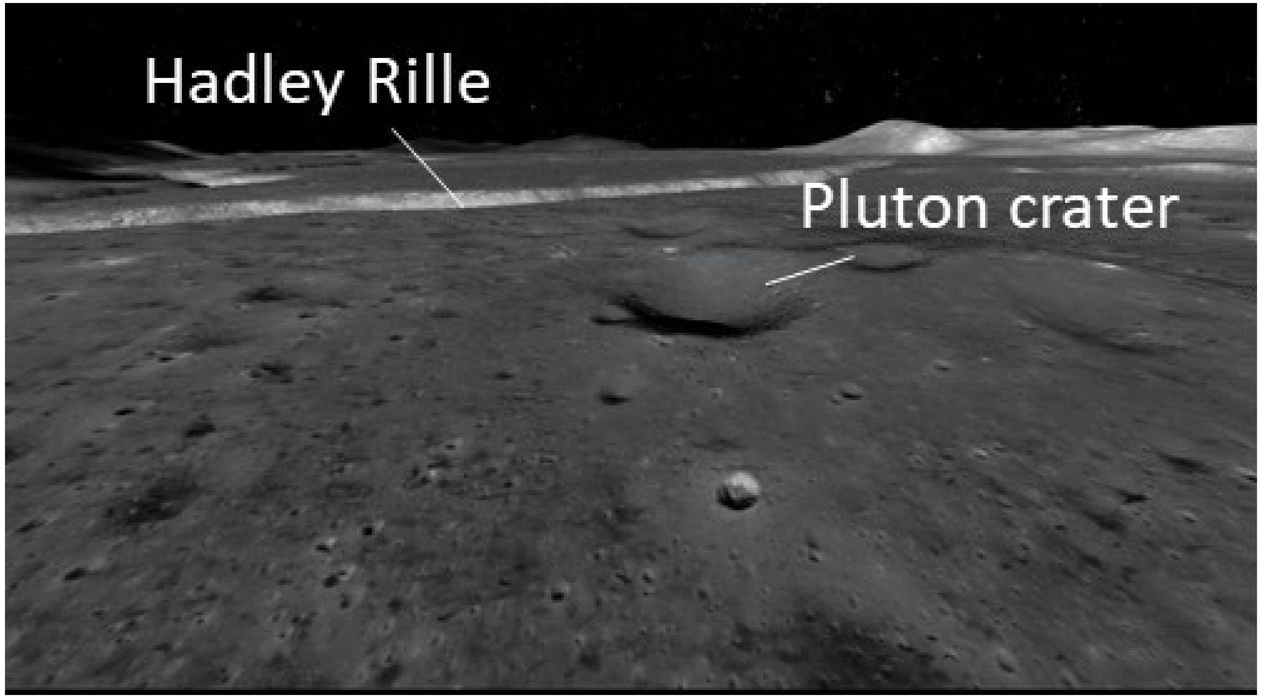
***Position and continue to hold hover cue over desired hover location*; control laws will bring vehicle to hover over desired hover location**

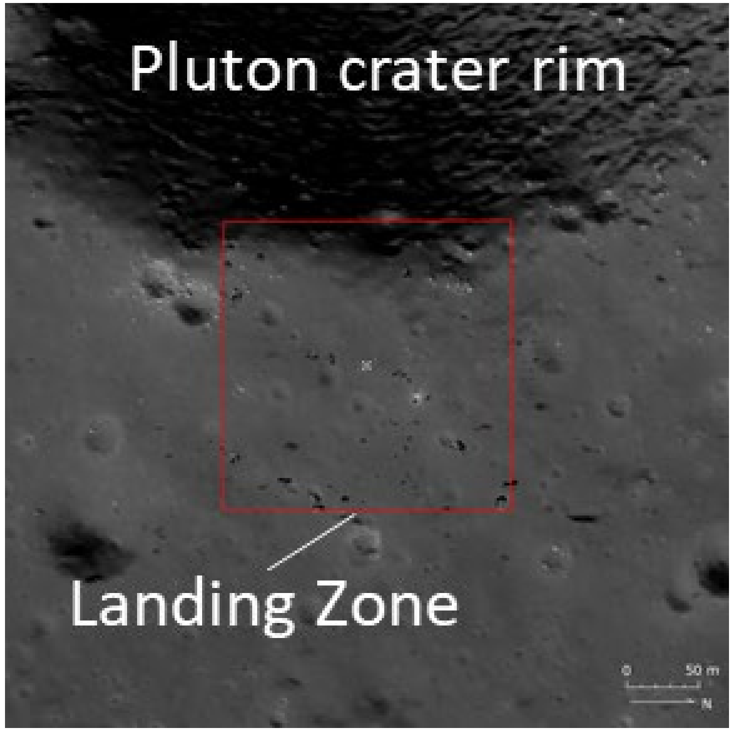
On Initial Approach

Don't chase LT; let the LT come to the hover cue (unless hover cue lags the velocity)



Landing Site Views





Landing site views – on approach (left picture) and from above (right picture)

Apollo Auto-Flight Operations

Number of Re-designation Commands Given during descent, after pitch-over

Flight	No of Re-designations (in P64)	Range Designations Displaced LM from Landing Site
11	Switched to P66 Early	- - -
12	7	- - -
14	1	2000 ft downrange, 300 ft North
15	18	1110 ft uprange, 1341 ft North
16	10	620 ft uprange, 635 ft South
17	8	- - -

P66 / Att Hold Takeover Altitude

Flight	P66 Height (ft)
11	**550**
12	**400**
14	**370**
15	**400**
16	**240**
17	**240**

Reference: *Digital Apollo: Human and Machine in Spaceflight*, Author: David A Mindell, The MIT Press, Cambridge, MA, 2008.

Ref: Major, L.M., Brady, T.M., and Paschall, II, S.C.: “Apollo Looking Forward: Crew Task Challenges.” paper presented at the 2009 IEEE Aerospace Conference, 7-14 March 2009

Experimental Matrix

Pilot Task- manually fly and land at redesignated landing target

3 runs flown for each control law (RCAH, ACVH) and control power (1.1, 2.9, 4.3 m/sec2) combination
1st run – 50m redesignation, practice run
2nd and 3rd runs – 75m red redesignation, after competing both runs give HQR rating and comments, NASA TLX workload ratings, Likert ratings

Runs blocked by control law
Runs blocked by control power
Control power blocks randomized within each control law block
Half pilots flew ACVH control block first, then RCAH block
Half pilot flew RCAH control block first, then ACVH block