Conceptual Human-System Interface Design for a Lunar Access Vehicle

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1 Introduction

1.1 The General Framework

In support of the vision for humans to establish a large scale, economically viable, permanent human settlement on the Moon within the next 25 years (Space Frontier Foundation, 2005), the next generation lunar landing vehicle must be capable of achieving pinpoint, anytime, anywhere safe landing on the lunar surface with high precision (10-100m). In addition, this vehicle should support both autonomous and manned lunar missions (NASA ASO-1160). Because of advances in technology over the past thirty-five years since the Apollo landings, the role of the human and automated systems in a new lunar lander system must be reevaluated and redesigned. This report details the design approach and resultant preliminary, conceptual design concepts for a Human-System Interface (H-SI) for a Lunar Access Vehicle (LAV).

While the primary focus of this report is the development of a H-SI concept to support astronauts physically located on a lunar lander, it is important to highlight that the design is intended to be adaptable to other control points (such as locally and distantly remote sites, e.g., from orbit or from earth). Developing a common display that can be used both in spacecraft as well as ground-based control sites is cost-effective in terms of equipment and personnel training, but common displays are also critical for shared situational awareness and collaboration across a network of both humans and automated agents.

The general human systems engineering approach taken in this project is illustrated in Figure 1. The Technology, Tasks, and Operators (TTO) triad represents an integrated and iterative approach to designing technology that will provide an interactive bridge between complex systems and humans engaged in supervisory control. In this framework, operators could be teams or individuals, and technologies are the artifacts that assist operators in accomplishing their tasks. Appropriate function allocation between operators and system is the underlining foundation for determining the role of human operators and desired technologies to support tasks. The general approach in the TTO framework for function allocation consists of distinguishing between the three major types of operator behavior: Skill-Based Behavior (SBB), Rule-Based Behavior (RBB) and Knowledge-Based Behavior (KBB) (Rasmussen, 1983).

- SBB: Behavior is automatic and doesn't require conscious thought or verbalization. For an example, keeping a car between lane lines while driving.
- RBB: Behavior becomes a conscious activity and is based on given rules. For example, using a checklist to fix a system problem.
- KBB: Behavior is based on the operator's knowledge (i.e. mental model) of the system and operating environment, and there are no, incomplete, or vague rules governing the process. KBBs usually occur in unknown, ill-defined urgent and emergent situations.

Although SBBs and some of the simplest RBBs can be fully automated, KBBs and most RBBs cannot be highly automated. Therefore, our primary focus for the LAV H-SI is to support KBB and RBB by providing operators with relevant technologies.

Three research methods are selected to achieve the TTO design goal. A cognitive task analysis bridges operators and tasks in the operational environment by understanding the local and global tasks that must be performed for mission success, as well as any environmental and organizational constraints. A sensor survey determines desired technologies which either exist or should exist, to support operator decision processes. Human-in-the-loop (HITL) testing is used to ensure that operators can utilize proposed technologies to achieve desired performance and to identify any cognitive issues not discovered in the cognitive task analysis. The ultimate goal is to develop technologies to support human operations within the context of overall successful mission/goal accomplishment. The requirements and specifications that support both operators and tasks will eventually drive the technology advancement by providing a core understanding of cognitive requirements through principled and comprehensive analysis.

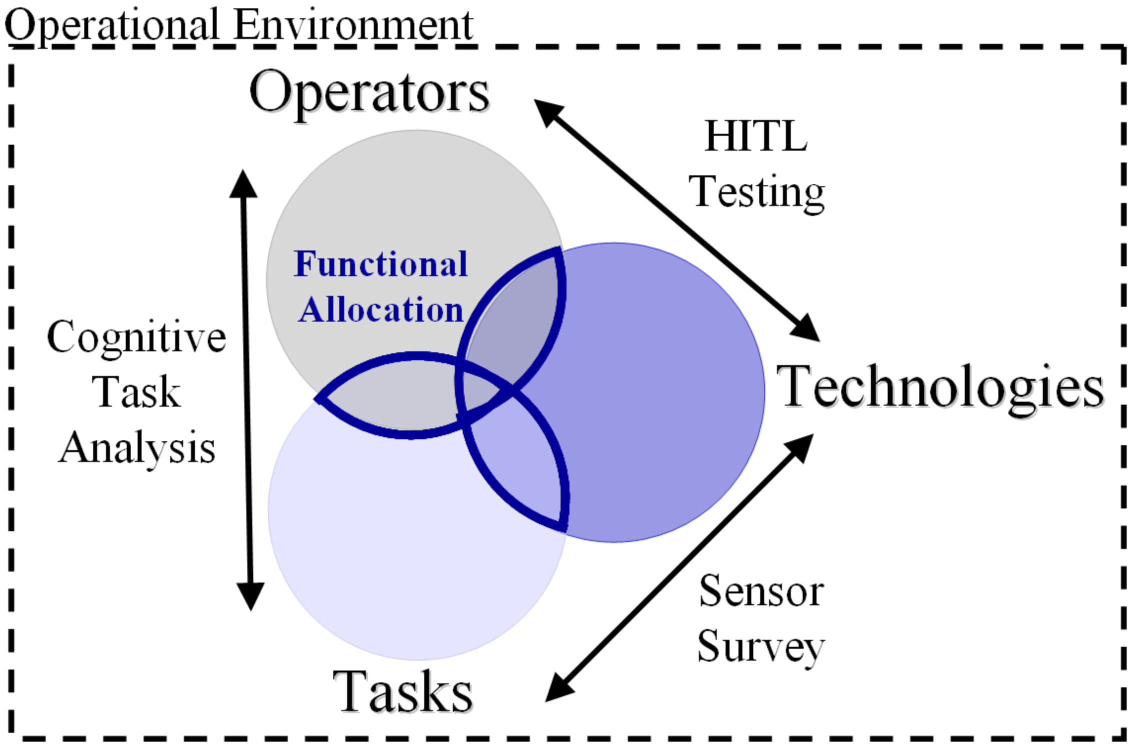


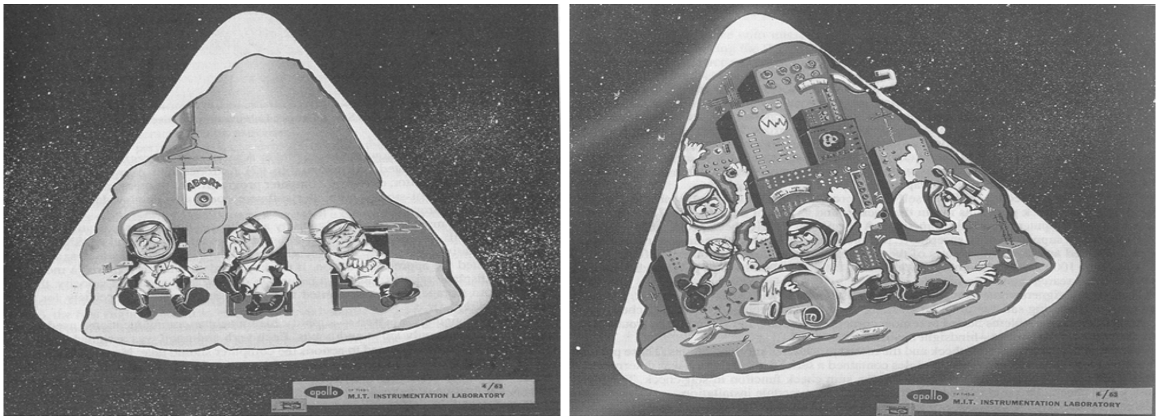
Figure 1 The TTO (Technology, Tasks, and Operators) Framework

1.2 Organization

This report has four sections. Section one is the general introduction of Lunar Access project. Section two introduces the background and motivation of the H-SI design. Section three provides H-SI conceptual designs. Section four discusses future issues and possible improvements. All the written documents produced from the TTO analysis are attached in this report as appendices. Acronyms and abbreviations in this report are listed in Appendix J Acronyms and Abbreviations.

2 H-SI Background and Motivation

Figure 2 presents two extreme cases of function allocation between Apollo astronauts and automated control systems. Despite its antiquity, the cartoon still depicts the primary concern for H-SI design more than forty years later. In a highly automated lunar lander Figure 2a), astronauts have essentially no tasking other than to make a single decision as to whether or not they should abort. However, when inserted into the control loop Figure 2b), astronauts struggle with the heavy operational workload. The crux of both the past and present H-SI design problem is to determine where, between these two points, the acceptable region exists and design accordingly. This problem is further complicated with the additional requirement that the next generation lunar lander system must support both autonomous and manned lunar missions.



a) Highly Automated Lunar Lander **b) Human Control in a Lunar Lander**

Figure 2 The Role of the Human & Automation in Lunar Landings

2.1 Apollo vs. LAV H-SI

The traditional H-SI of an Apollo lunar lander (ApLL) was primarily composed of physical instruments such as pressure gauges, thermometers and switches (Figure 3). These electro-mechanical displays and controls present a major challenge for human operators because there were several of these types of displays and controls, and each of them required an operator's attention at a certain time point. So an operator had to memorize their locations and operational sequences through specialized training. Fortunately, with the rapid development of computer hardware and software technologies, on-screen virtual displays and controls are replacing physical displays and controls. This means that humans are able to operate the physical system via a human-computer interface (i.e. computer screen and mouse). Because of the proposed use of a “glass cockpit”, the LAV H-SI has several prominent advantages over the ApLL H-SI:

- upgradeable software agents to support human decision making and situation awareness which provide for a more robust and cost-effective system
- provide on-demand information in desired locations
- reduced weight because individual physical instruments are replaced by an integrated display
- better information access, integration, and sharing
- displays are multi-purpose in that they can be used by any human controller at any access point, i.e., on the lander, from a local remote control point such as on orbit, or from a distance remote control point such as earth-based mission control.

Figure 3 Displays and Controls in an Apollo Lunar Lander

2.2 Apollo vs. Lunar Access Requirements

Based on interviews with Apollo astronauts and Apollo mission assessment, we found several critical drawbacks in the Apollo H-SI design (Draper, 2005; Newman et al., 2005).

- In Apollo missions, astronauts had to rely on significant mental calculation and rough estimation to identify possible landing areas, known as landing footprint.

- Apollo astronauts also had to memorize an inordinate number of procedures and operational information. This required several years of highly specialized training.
- It was difficult for astronauts to sense sink rate and lateral motion of ApLL.
- Only limited landing site re-designation options were available due to the geometric constrains of Lunar Module (LM) windows.
- Landing accuracy was a problematic issue for Apollo missions due to lack of terrain information of lunar surface (Appendix I Landing on the Moon: Comparison between Apollo-era and Lunar Access Project)

These issues must be addressed in the LAV H-SI design. We propose the following key functional requirements for the LAV H-SI design:

- Astronauts/controllers should be constantly aware of vehicle endurance and windows of opportunity for landing, both in time and space.
- Software agents (e.g., on-screen smart checklists) must be provided to reduce astronaut/controller cognitive workload
- Provide advanced visualization tools (i.e., synthetic and predictive views) to enhance astronaut/controller situation awareness.
- On-demand information access and sharing among crew members and mission controllers
- The H-SI should be reconfigurable to support various system configurations (i.e., crew positions & assignment of personnel)

3 The LAV Conceptual Prototype

3.1 HS-I Design Assumptions

The key design assumptions for the LAV H-SI conceptual prototype are:

- Crew assumptions:
    - There are 2 crew members actively involved in monitoring and decision making of the vehicle position and state during lunar landing
        - However, the displays designed in this effort are intended to be used by an operator/controller in the control loop such as ground control. This assumption should not be misconstrued as a requirement.
    - The 2 crew members are seated with the displays in front of them
    - The crew will not be able to control the vehicle during the braking phase
    - Manual control will only be used during off-nominal situations.
        - Due to time constraints, actual manual control activation will not be explored in year 1.
    - The crew will be positioned so that the g-loading will be positive during coast and braking burn.
    - The displays should support the landing without the need for ground control.
- Landing site assumptions:

    - A single landing site will be selected *a priori* and the crew will only be able to redesignate to areas within the local landing region surrounding the specified landing site
    - The crew will only be able to abort to orbit or abort to a landing site within the local landing region surrounding the specified landing site
    - There is *a priori* knowledge of the location of the desired landing position and surrounding hazards
        - Thus some level of mapping exists
    - There is prior knowledge of an approximate elevation profile
- "Window" assumptions:
    - A sensor, such as a monocular camera, will provide a synthetic "out the window" view
    - A window is not required for determining vehicle position and state and is not needed for a lunar landing.
- LIDAR assumptions:
    - The LIDAR will provide real time lateral and vertical position information during coast and braking burn
    - The LIDAR will provide information about hazards within the landing region during the terminal descent

3.2 The Conceptual Prototype

Based on the initial results of Apollo mission assessment, an incomplete sensor survey, a cognitive task analysis, and a proposed Lunar Access trajectory, a preliminary H-SI design is proposed in Figure 4. The H-SI prototype is composed of three displays: landing zone, situation awareness, and system status. The partitioning of display information across three different displays represents the three primary elements of human supervisory control on the LAV: 1) Observing the automation's attempt to conduct a precision landing and intervening if necessary, 2) Understanding where in space and time the current LAV is in the landing sequence and what future states/actions will occur, and 3) Monitoring of LAV systems in the event of an urgent or emergent condition that could cause an abort of the landing sequence. While this preliminary display concept represents these three primary tasks on three screens, as will be depicted in later sections, the actual displays are designed in a modular format such that the information can be spread across multiple screens. This modular design approach is critical given that no data yet exists on vehicle or cockpit configuration. Moreover, we recognize that crew position is still an unknown.

As stated in the assumptions, there is no reliance on a traditional window in this design. A windowless cockpit with a synthetic vision display has been proposed for designing Moon/Mars vehicles (Oman, 2005). This design concept offers important advantages (e.g. supra-normal acuity and wider functional field of view) over windows and direct human vision. It also supports various vehicle configurations and crew positions. Therefore, we have incorporated this new design concept in our H-SI conceptual prototype.

For the purposed of this preliminary design effort, we selected a 2 astronaut crew configuration (a pilot and a systems support co-pilot) because a) this was the configuration for Apollo, and b) this is also the traditional configuration for current airplane cockpits. In Apollo missions, the Commander (CMDR) was actual the landing pilot who needs to see the landing site and the Lunar Modal Pilot (LMP) monitored the systems' status. However, despite the initial crew assignment of 2, as discussed previously, this display configuration is intended to be used by any controller in the loop who could be on the LAV or on the earth, thus it is not role specific. Moreover, because of the modular design of the display components, role allocation is not permanent and is easily reconfigurable. In years 2 and 3 of this research effort, role allocation should be further investigated to include:

- What other viable role allocation schemes exist?
- How many people are really needed in the lunar landing process? It could be that with advanced automation, only one person instead of two is needed.
- If the crew assignment shifts to one or more ground/remote controllers, how will the display designs need to change to support issues such as time latency and control authority?

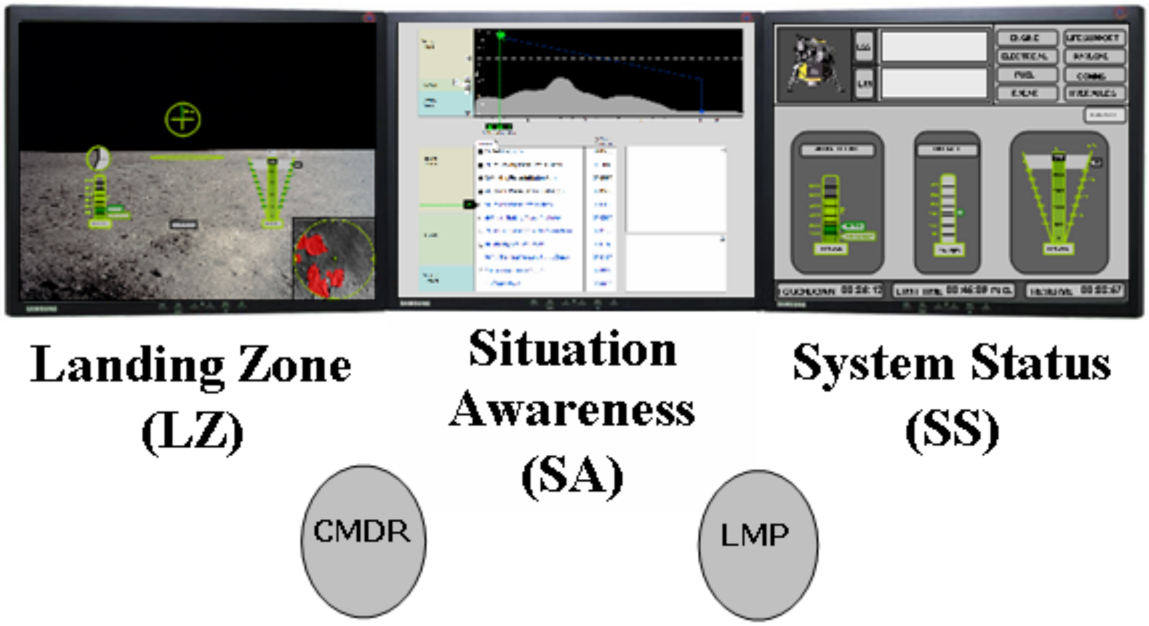


Figure 4 The Conceptual, Preliminary H-SI Design

3.3 Landing Zone (LZ) Display

3.3.1 LZ Display Introduction

While much of the design of the LAV displays will be based on display technologies utilized in other domains, a Moon landing is a very different challenge. The lunar terrain, trajectories, vertical descent to landing, and the role of the crew, when considered all together, make landing on the Moon dissimilar in several ways to flying an airplane, maneuvering an underwater vehicle, or landing a helicopter. The focus of this section is the development of the displays for the actual landing sequence, to include redesignation of the previously selected landing site. It will be crucial to provide the astronauts with a view of where they are headed along with critical information necessary for monitoring the current situation, redesignating a landing site if necessary, or taking over manual control in extreme circumstances. The Landing Zone (LZ) display is designed primarily for the crew member who will be responsible for redesignating a landing site or taking over manual control if necessary. For Apollo missions, this role belonged to the mission commander, but may or may not be the case for the LAV.

3.3.2 Motivation and Objectives

Results of a cognitive task analysis identified several areas needed for improvement over Apollo in terms of the information provided to the crew about their landing site and vehicle capability. We propose that these major areas, which will be discussed below, are:

- Landing Window of Opportunity
- Over-reliance on Memory
- Lack of Peripheral and Depth Perception Cues
- Landing Site Redesignation Issues

3.3.2.1 Landing Window of Opportunity

One issue that was identified was an awareness of the vehicle's endurance in reaching alternate landing sites if necessary. Research prior to the first lunar landing demonstrated that the window of opportunity for redesignation was a function of current altitude, fuel, window geometry, surface lighting, and vehicle attitude (NASA, 1966). For a human, combining these factors mentally and reaching a decision using constantly changing variables adds significant mental workload. An interview with Buzz Aldrin revealed that the primary consideration of the crew in reaching an understanding of current vehicle redesignation capability was fuel and the astronauts relied heavily on their memory and prior training experiences to understand limitations (Appendix A Interviews, Conversations, and Meetings). In a phone interview with John Young, he also touched on this fact. He said "We practiced this whole business many, many times…thousands of time. I probably had about 40 or 50 landing in the Lunar Training Vehicle. So, you know, we practiced and the Lunar Training Vehicle ran out of gas fast too…it didn't have much gas either" (Appendix A Interviews, Conversations, and Meetings). This demonstrates that fuel was the driving factor in the minds of the Apollo astronauts for determining the landing site window of opportunity.

The window of opportunity for landing is analogous to what VTOL (vertical takeoff and landing) aircraft also must consider. During a visit to Cherry Point and New River Marine Air Stations, AV-8B Harrier and MV-22 Osprey pilots explained how they know their time and available window for landing. They explained that it was purely something that they had a feel for from significant training. They also explained that they know their fuel and burn rate (which are constantly changing) and can use the combination of that information to determine capability to some rough degree (Appendix A Interviews, Conversations, and Meetings).

It is important to note that fuel is a critical limiting factor for a lunar landing and relying on heuristics and correct mental calculations for such a critical event represents a significant design flaw. Thus this research has identified the need to make the crew continuously aware of this dynamic window of opportunity for landing, taking into consideration all the variables for a landing site redesignation.

3.3.2.2 Over-reliance on Memory

Another issue that was identified through the cognitive task analysis and was touched on in the interviews is the fact that the astronauts were constantly pulling vital information from their memories. Operators should not have to determine courses of action through calculation, inference, and data transformation because this process is inherently error-prone (Lintern, Waite, & Talleur, 1999). Instead of relying on memory which is inherently a flawed especially under time pressure (Wickens & Hollands, 2000), humans engaged in supervisory control should be provided with direct perception-action visual representations. Direct manipulation interfaces allow operators the ability to directly perceive the system state, make correct decisions, and reduce errors (Rasmussen, 1998; Shneiderman, 1998). Therefore, a major objective of this LZ display is to provide the commander with as much direct perception-action information as is necessary to safely and accurately land, while avoiding information overload and reliance on memory items. This integrated information, including real and synthetic “out-the-window” views, will allow the crew to perceive the surroundings and make judgments based on that direct perception interaction rather than pulling from memory.

3.3.2.3 Lack of Peripheral and Depth Perception Cues

An issue that repeatedly came up in interviews was the issue of relative size and depth perception. The following quote from an interview with Charles Duke, the Lunar Module Pilot for Apollo 16, illustrates this issue:

> “At the beginning, when we looked at the rock, we didn’t think it was very large. The problem on the Moon is depth perception. You’re looking at an object that you’ve never seen before and there is no familiar scale. By that I mean you don’t have telephone poles or trees or cars with which to judge relative size. As you look at a rock, it looks like a rock. It could be a giant rock far away or it could be a smaller rock close in. We thought it was an average size rock. We went off and we jogged and finally got down there and the thing was enormous. I imagine it was 90 feet across and 45 feet high. It was like a small apartment building towering above us as we finally got down there. I believe it was the largest individual rock anybody saw on the Moon.” (McCandless, McCann, & Hilty, 2003)

This lack of depth perception cues can make obstacle and hazard identification difficult as well as perceiving lateral and vertical rates. Unfortunately, these are key pieces of information that many earth-based vertical landing aircraft pilots depend on to make a safe landing. An AV-8B Harrier pilot described how he maneuvers the vehicle such that he can see two large landmarks out his window. He then primarily uses these landmarks to sense his sink rate and any horizontal movement. He also looks out his window to be sure that the landing site is clear of major debris that may inhibit a safe landing (Appendix A Interviews, Conversations, and Meetings). Because of the windowless cockpit design as well as the lack of perceptual cues, this critical information must be displayed to the crew of a lunar lander in another way such that images seen through live video feed or synthetic images do not hinder the ability to safely land the vehicle either autonomously or manually.

3.3.2.4 Landing Site Redesignation Issues

For Apollo astronauts, landing site redesignation was a complicated process that introduced significant potential for error. Landing site redesignation was accomplished using the LPD (Landing Point Designator), which was difficult (Jones, 2000). Use of the LPD involved using the scribe marks etched in the double panes of glass of the commander's small window, and numbers provided by the guidance system on the DSKY (Display and Keyboard). As illustrated in Figure 5, these etchings provided a reticle that was used to determine where the Lunar Module would land.

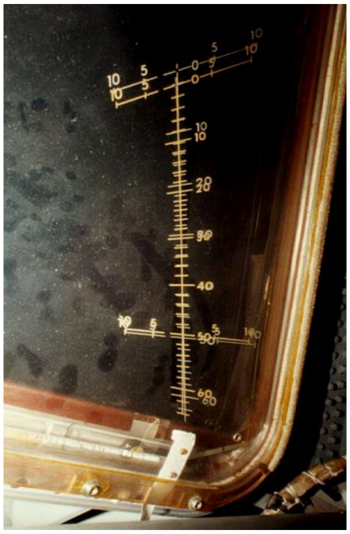


Figure 5 LM Window (Jones, 2000)

A description by Eugene Cernan, the Apollo 17 mission commander, explains how the reticle was used:

> "In addition to all the fancy gear, all the rate needles and everything, when it came right down to landing, we had etchings on the window in both pitch and yaw. And here, after pitchover, Jack is telling me where on the window the computer thinks we're going to land. The digital autopilot and the computer programs were designed to accept attitude impulses with my hand-controller. I could go "blip"

> once and that would tell the computer that I wanted to change the target maybe a half degree or a degree in pitch. … It was the same sort of thing in yaw, but you have to remember that yaw didn't directly change the flight direction because yaw is a rotation around the thrust axis. …So if I blipped the hand-controller in yaw, what it really said to the computer was that I wanted to land a little left and that it had to do a little roll to get over there" (Jones, 2000).

Disorientation with respect to current position and desired landing point was another factor that made landing resignation difficult. An interview with Pete Conrad, who was the mission commander for Apollo 12, revealed that right after pitchover and upon his first view of the landing site, he was completely disoriented. He said "When the LM pitched up at 7,500, I didn't have the foggiest idea where I was. There were 10,000 craters out there" (McCandless, McCann, & Hilty, 2003). As a result of this disorientation, Pete Conrad and Allan Bean landed the LM primarily using Instrument Flight Rules (IFR) With only a few minutes between the first view of the landing site and touchdown, it is critical that the crew be aware of not only where they are, but where they are headed, and thus any time spent reorienting to the environment takes away from time needed for landing site redesignation. Thus the proposed landing zone display in this report seeks to eliminate any time in which the human is temporarily removed from the loop due to disorientation.

To determine specifically what data and information are needed by pilots/controllers attempting to redesignate a lunar landing site, decision ladders were constructed (Appendix E Decision Ladders). Decision ladders are modeling tools that capture the states of knowledge and information-processing activities necessary to reach a decision. Decision ladders can help identify the information that either the automation and/or the human will need to perform or monitor a task. Decision ladders for the decisions to redesignate a landing site and possibly take over manual control were constructed to identify display information requirements as well as potential human-automation allocation strategies. These decision ladders, outlined in Appendix E Decision Ladders, illustrate the need not only for the same information identified by the cognitive task analysis, but the need for several other pieces of information such as the need for visual or oral alerts in certain situations, obstacle and hazard identification including descriptive parameters, preferred alternate landing areas, the current vehicle footprint capability, and feedback on the vehicle path in terms of changing key parameters such as fuel, rates, and position.

The list below outlines the key objectives of the landing zone display. Some of these objectives may be applicable to the other displays as well.

1) Provide the commander (or crew equivalent) with all of the critical landing parameters in a heads-up display format.
2) Provide the crew with the ability to perform *precision* landing at a desirable landing site
3) Reduce the time that human is out of the loop due to disorientation.
4) Provide the commander (or crew equivalent) with as much information as is necessary to safely and accurately land the lunar lander, while avoiding information overload.

5) Combine and condense the information in such a way that it provides critical information in its most applicable form.
6) Provide the ability for the crew to *perceive* their surroundings instead of pull from their memories in order to make judgments and key decisions.
7) Make the crew continuously aware of the regularly changing window of opportunity for landing, taking into consideration all the dynamic factors.
8) Provide the astronauts with a view of where they are headed along with critical information necessary for monitoring the current situation, redesignating a landing site if necessary, or taking over manual control in extreme circumstances.
9) Provide information that is not provided by visual cues for on the Moon due to lighting and depth perception issues.
10) Provide a tool to aid with depth perception and relative size identification during landing.
11) Identify obstacles and/or hazards quickly and sufficiently.

3.3.3 LZ Display Design

The LAV LZ display should capture the most critical information needed to perform a safe and precise lunar landing. Through the aforementioned cognitive task analysis, several key pieces of information were identified as necessary to either monitor or perform a precise and safe lunar landing. These elements include altitude, sink rate (vertical velocity), fuel, and attitude, thrust level, lateral and forward and aft rates, and landing site location. For Apollo commanders, most of this information was available across multiple gauges within the cockpit, but they relied on their Lunar Module pilots (LMP) to read much of this information to them while they maintained an "out-the-window" view of the landing site (McCandless, McCann, & Hilty, 2003). Jack Schmitt explained a similar role and even commented on the fact that had the technology been available at the time, a heads-up display that provided the commander with all the information he depended on his pilot for would have been very beneficial (Appendix A Interviews, Conversations, and Meetings). Therefore, one objective of this display is to provide the commander with all of the information that he/she needs in a heads-up display format.

Figure 6 illustrates a screen shot of the LZ display with the landing zone in the distance. The LZ display includes four major elements. The first is the fuel and thrust level gauge that indicates fuel levels to include hover and emergency fuel as well as the current thrust level of the engine(s). The second element is the Vertical Velocity and Altitude Indicator (VAVI) that conveys altitude and sink rate information as well as important hover situations. Next, the velocity vector which indicates the direction and rate of the vehicle's movement. Finally, the top-down view illustrates the intended landing zone around the landing site and window of opportunity while including important hazard information. The various elements and modes of the preliminary LZ display will be described in detail below.

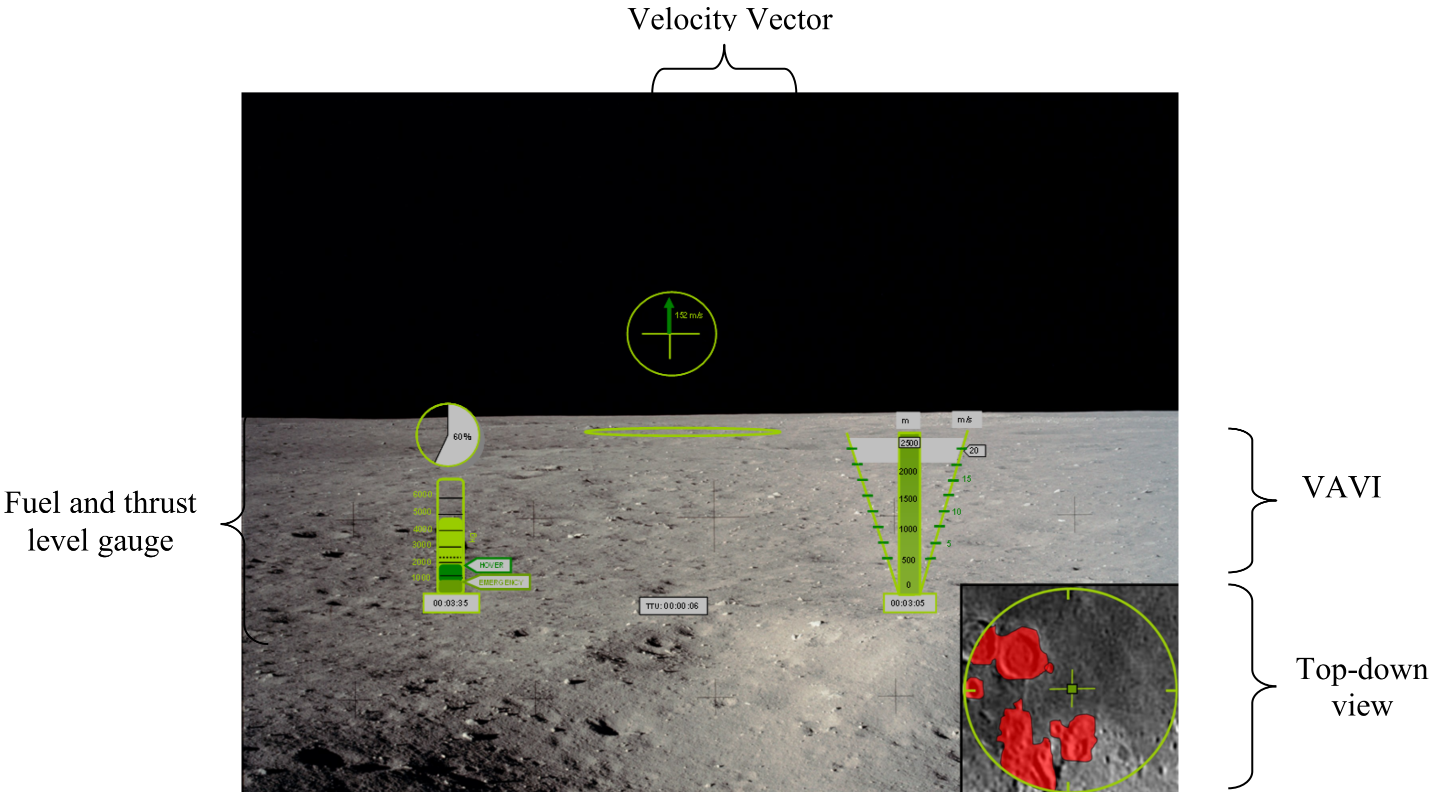


Figure 6 LZ Display Screen Shot

3.3.3.1 Vertical Altitude and Velocity Indicator (VAVI)

The vertical altitude and velocity indicator (VAVI) conveys both altitude and sink rate (also known as vertical velocity) information in a single display[1]. Apollo landers did and current VTOL aircraft still display this information separately which requires the pilot to make mental calculations in order to draw meaningful conclusions. The VAVI is capable of indicating intended descent rates, unsafe situations, and hover maneuvers in a condensed form. The most recent version of the VAVI, which has not yet been integrated into the screen shots, provides a better visual of the vehicle's current condition and hover maneuvers. In Figure 7, the vertical bar indicates altitude while the "wings" that come out from the altitude bar at the current altitude, act as needles for the sink rate dial to the right. A nominal descent is illustrated in Figure 7a, while a hover initiation, hover, and unsafe sink rate are illustrated in b, c, and d respectively. The grey band again indicates the intended descent rate range, while the red illustrate an unsafe sink rate for that current altitude. The black "wings" of the VAVI act as the needles of the descent rate dial. The rate range band becomes shaded when the descent rate sinks below the intended value, indicating the initiation of a hover (Figure 7b). Finally, completely horizontal wings indicate that the vehicle is in a true hover at its current altitude (Figure 7c), but should also be completely horizontal on landing. Unsafe descent rates are indicated by the estimated time to touchdown box turning red as well as the unsafe sink rate that the vehicle is

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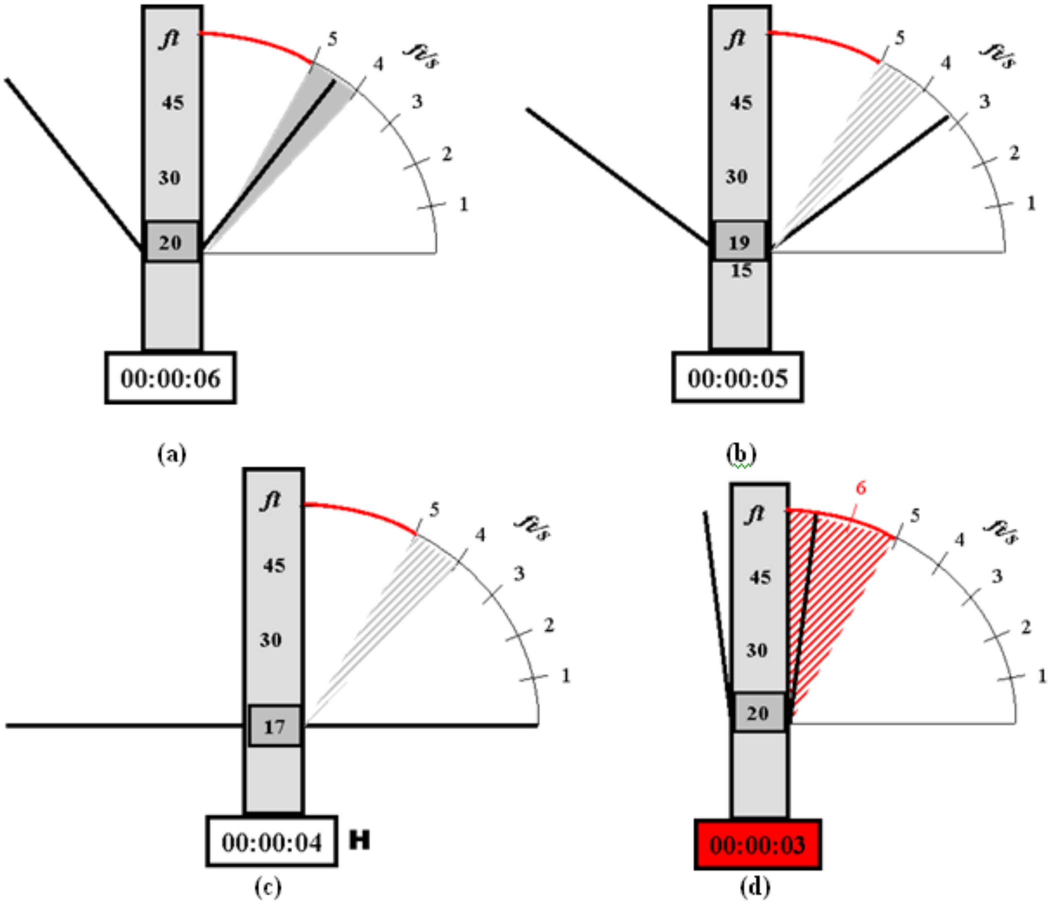
[1] A patent application is pending for the VAVI.

experiencing. As the entire VAVI is dynamic, it is an integrated velocity vector that provides the direct-perception interaction described previously.



(a) (b) (c) (d)

Figure 7 VAVI

3.3.3.2 Fuel and Thrust Gauge

The fuel gauge, located in the lower left corner of the display and depicted in Figure 8, conveys import fuel information. The light green color fuel is the current amount of fuel that the vehicle has. The black dotted line indicates the amount of fuel that the vehicle will land with, should it land at the targeted site with no redesignations. The dark green fuel is a pre-determined desired amount of hover fuel. If a hover is commanded, the level of this fuel will decrease, causing the entire fuel level to drop. Finally, the medium-dark green fuel is the emergency fuel. The number along the vertical axis of the gauge is the raw amount of fuel left, while the time at the bottom is the combination of the burn rate and raw fuel level into an available burn time. The circle above the fuel gauge indicates the thrust level. It is important to note here, that these illustrations are only sketches and thus the colors and markers will likely change in the final demonstration.

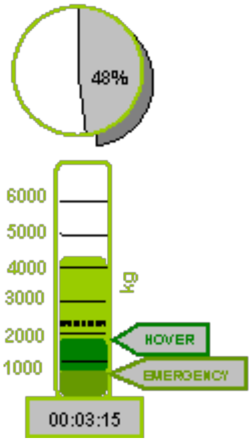


Figure 8 Fuel and Thrust Gauge

3.3.3.3 Pitch Ladder

A traditional pitch ladder appears in the terminal descent phase in order to monitor the vehicle's attitude during the final touchdown. Should the crew have to take over manual control, this would also be a key tool to perform a safe landing. The long, solid straight line indicates the horizon. Each hash line is five degrees of pitch with the solid lines indicating a positive pitch and the dotted lines below the horizon indicating a negative pitch. The lunar lander icon in the middle will move up and down this pitch ladder to indicate current pitch attitude. Finally, the roll of the icon also indicates the roll of the vehicle. A screen shot of this is depicted in Figure 9 below.

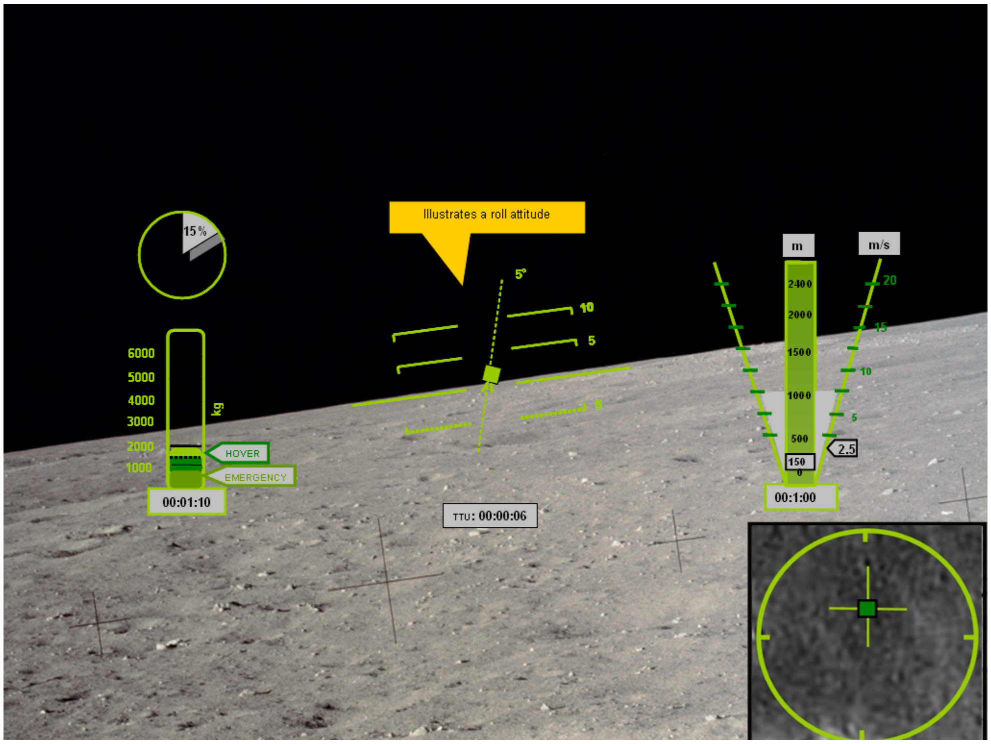


Figure 9 Roll Attitude Display

The option will also be given to the crew to move the top-down view to the lower right corner during terminal descent, allowing the horizon of the pitch ladder to match the horizon of the "out-the-window" view.

3.3.3.4 Landing Zone Forward-Looking View

The LZ forward-looking view is available to the crew at the start of pitchover. In addition to the fixed elements described above, this view, illustrated in Figure 10, provides an *a priori* map of the landing zone including predetermined hazards in the area in the lower right corner. In this view also, the velocity vector is indicated in a circle at the top of the display. This circle represents the spacecraft bore sight and the arrow pointing in the upper right quadrant indicates that the vehicle is moving forward and to the right at the digitally displayed speed next to the arrow. The length of the arrow moves relative to the magnitude of the ground speed. The landing zone, seen in the distance as an oval, also indicates the targeted landing site by a dark green square. As the spacecraft approaches pitchover, the bore sight will drop until a predetermined angle below the horizon, at which time the landing zone view would replace it and the pitch ladder would appear.

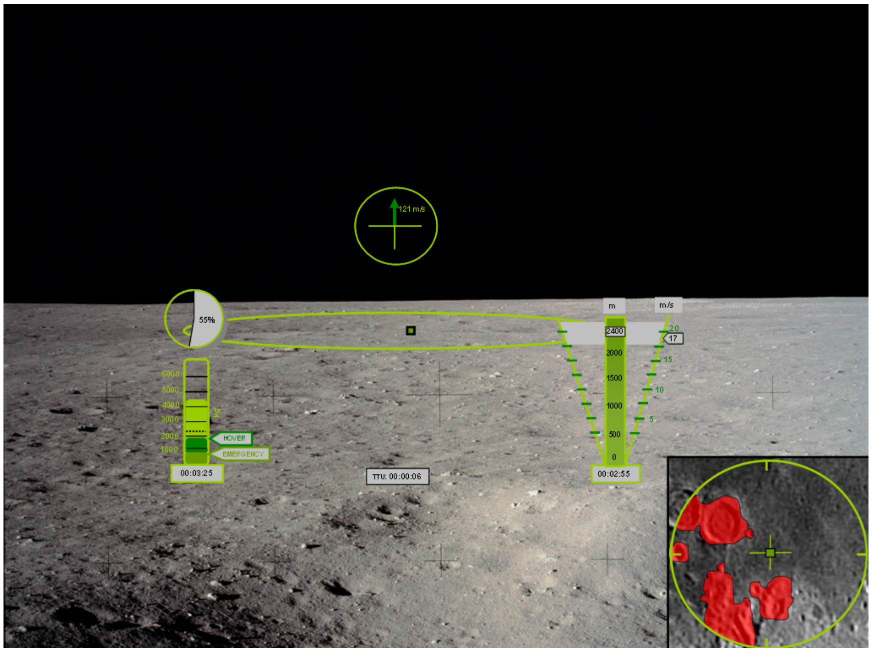


Figure 10 LZ Forward-Looking View

3.3.3.5 Landing Zone Top-Down View

The LZ top-down view provides critical landing zone information. This view transitions from the lower right corner to the center of the display once the vehicle is positioned directly above the landing site and has completed its pitching maneuver (Figure 11). The rationale behind this view is that once the vehicle is directly above the landing site, the information about the landing zone below it is the most important information for the terminal descent phase. This design was adapted from the MV-22 Osprey displays in which top-down information is overlaid over an “out-the-window” view (Appendix A Interviews, Conversations, and Meetings). According to an MV-22 Osprey instructor pilot, the pilots love this orientation and find it very intuitive (Appendix A Interviews, Conversations, and Meetings).

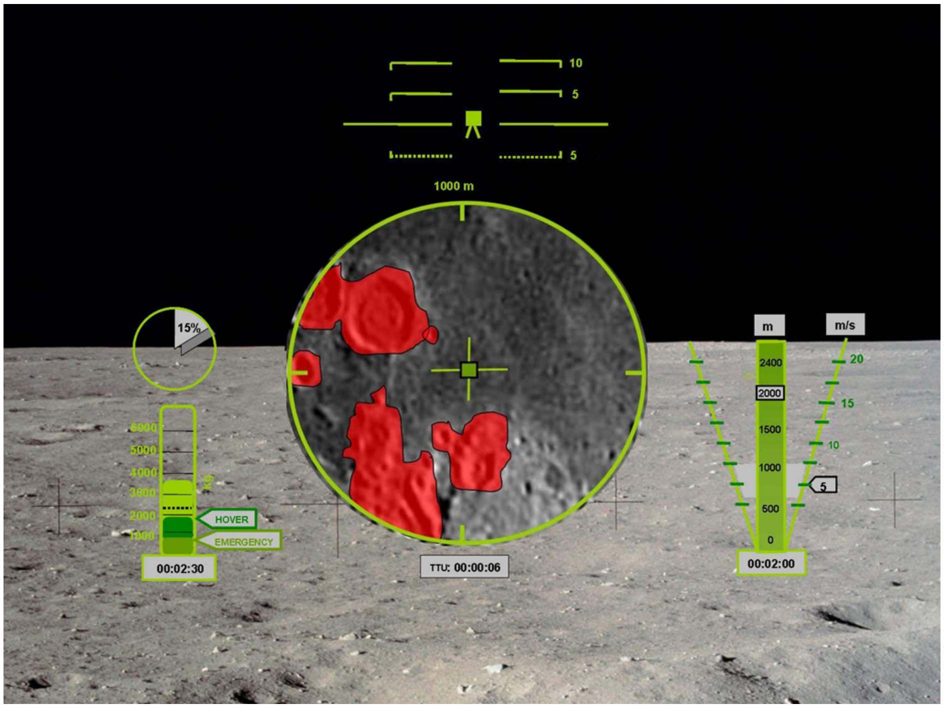


Figure 11 Top-Down View of Landing Zone

Important additional information included in this view is the velocity vector, and the landing footprint for window of opportunity and hazard detection and avoidance information. In this phase of the landing, the Terminal Descent Phase, the velocity vector is superimposed over the top-down view. The bars of the cross in the center of the circle indicate forward, aft, and left and right velocities. This same notation as the forward-looking view holds here as well. This superimposed velocity vector is illustrated in Figure 12 below.

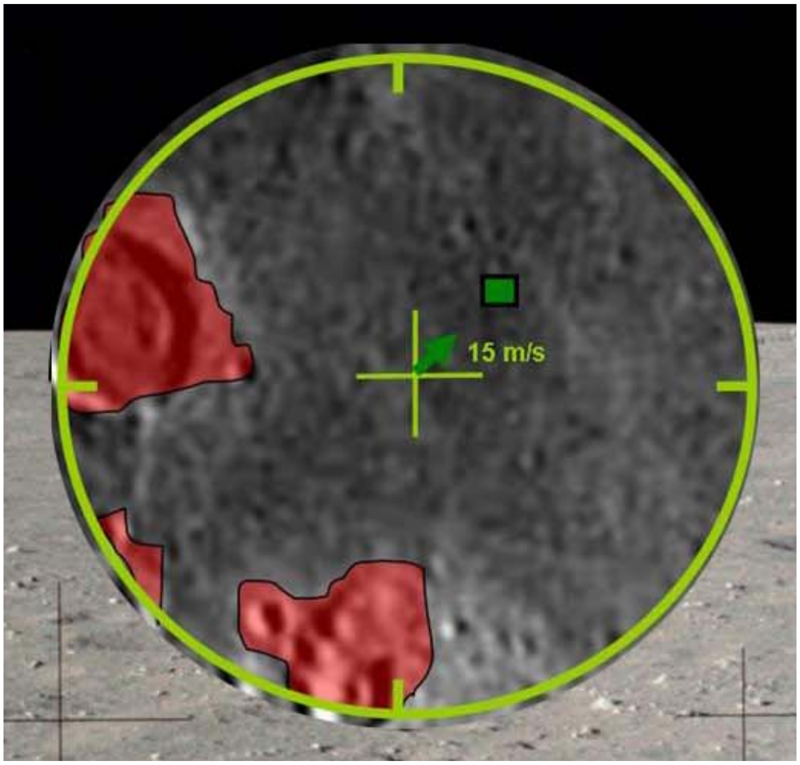


Figure 12 Velocity Vector Superimposed on Top-Down View

The landing zone is a window of opportunity for landing site redesignation and includes the area that is within reach of the vehicle. It is indicated by the green circle seen in Figure 11. Since the size of this window of opportunity is a function of vehicle altitude and fuel constraints, it will constantly be shrinking during a descent. The number seen directly above the top-down view is the diameter of the green circle. Other distance indicators such as small hash marks in the circle may be added for scale issues.

The top-down view of the landing zone, provided no later than the beginning of the terminal descent phase, also provides hazard detection information. Provided primarily by the LIDAR, the red areas indicate obstacles or hazards. This information will be used by the crew to determine if a landing site redesignation is necessary. The grey box below the top-down view illustrated in Figure 11 is the time until an update of the sensor image that is providing the top-down view.

3.3.3.6 Redesignation Mode

When the LIDAR indicates that the targeted landing site is hazardous and the human intervenes to redesignate a landing site, several part of the display will change to indicate a mode change and prevent mode confusion. Figure 13 illustrates a screen shot of the display in redesignation mode. The primary elements of this mode are the blue cross-hairs that appear to allow for redesignation and the 2nd fuel gauge which also shows a fuel level in blue. The blue cross-hairs are controlled using a cursor input device that has yet to be designed. Once the cross hairs are over a new safe landing site, the site is confirmed with some activation of the cursor device. The blue square at the center of the blue cross-hairs will become dark green when the system successfully targets the new landing site.

The second fuel gauge that appears during redesignation mode shows a blue fuel level, which indicates the amount of fuel that will be remaining on landing for the new redesignation site. In other words, if the user places the blue cross-hairs over the originally targeted site, the blue fuel level should match the black dotted line on the constant fuel gauge. If the blue cross-hairs are placed on the edge of the green circle, the blue fuel gauge should show an empty tank. The time associated with the redesignation mode fuel gauge is the amount of burn time associated with the level of fuel that will be remaining when the vehicle lands. For example, if the time below the redesignation fuel gauge reads 00:00:15, it indicates that the vehicle will land with approximately 15 seconds worth of fuel remaining if the landing site is redesignated to the current blue cursor position. Similar to the blue cross-hairs, once the redesignated site has been accepted by the system, the redesignation fuel gauge will disappear to indicate another mode change. The black dotted line on the nominal fuel gauge, indicating extra fuel at landing, will move to be consistent with the new landing site.

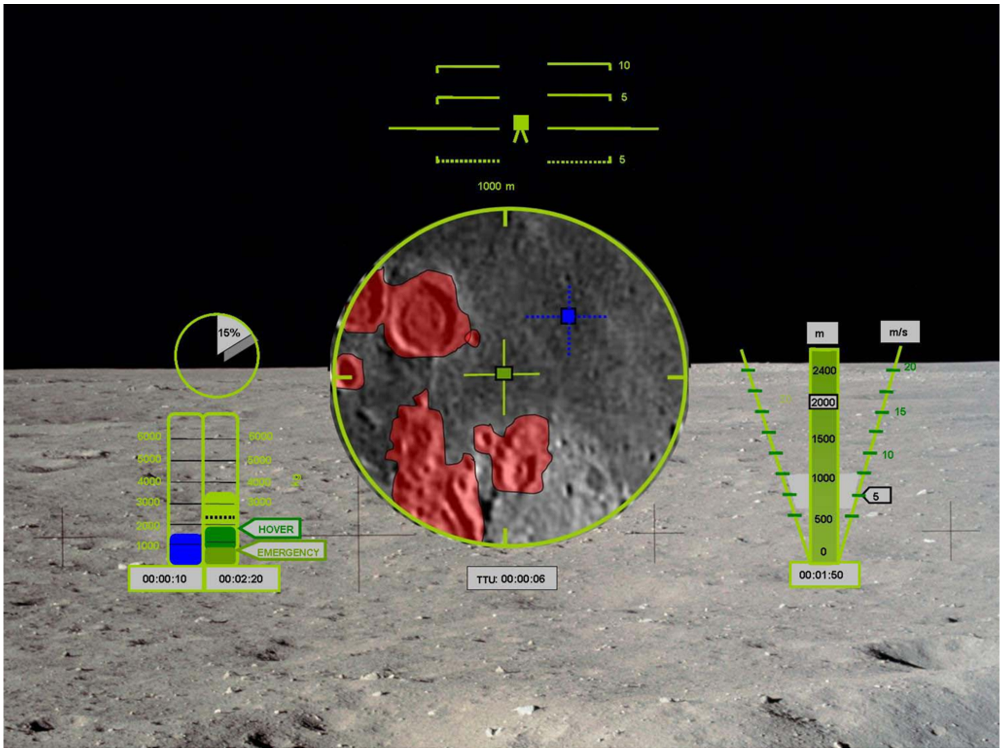


Figure 13 Redesignation Mode

3.3.4 LZ Display Issues

There are several issues that still require some research and application in the landing zone display:

- Map-tie error. Based on the current state of maps of the lunar surface, there is a good chance that upon pitchover of the LAV, sensor data may indicate that the *a priori* map is not concurrent with the current position of the vehicle. Further research and discussion needs to be devoted to determining how to deal with this situation.
- Obstacle visualization. In the current display design, major obstacles such as craters are outlined in red. However, it has not been determined how point obstacles should be handled. These include small rocks that may hinder a safe landing. This decision may largely be a function of the sensor technology, namely LIDAR, which will be used to survey the landing site.
- Depth perception cues. The addition of a synthetic icon of a familiar landmark that will provide the crew with a relative size indicator straight on the landing zone display. This is to accommodate the very severe issue of depth perception and relative size outlined by the Apollo astronauts.
- View Angles. When providing the crew with the “out-the-window” forward-looking view, there is a range of view angles that could be provided inside the cockpit. The best angle for this view is another parameter that needs to be determined.
- Braking Phase View. The landing zone display currently only covers the time frame from pitchover to landing. Determining what information and in what format that information should be displayed to the crew during the braking phase is another important research area that will be focused on in the future.

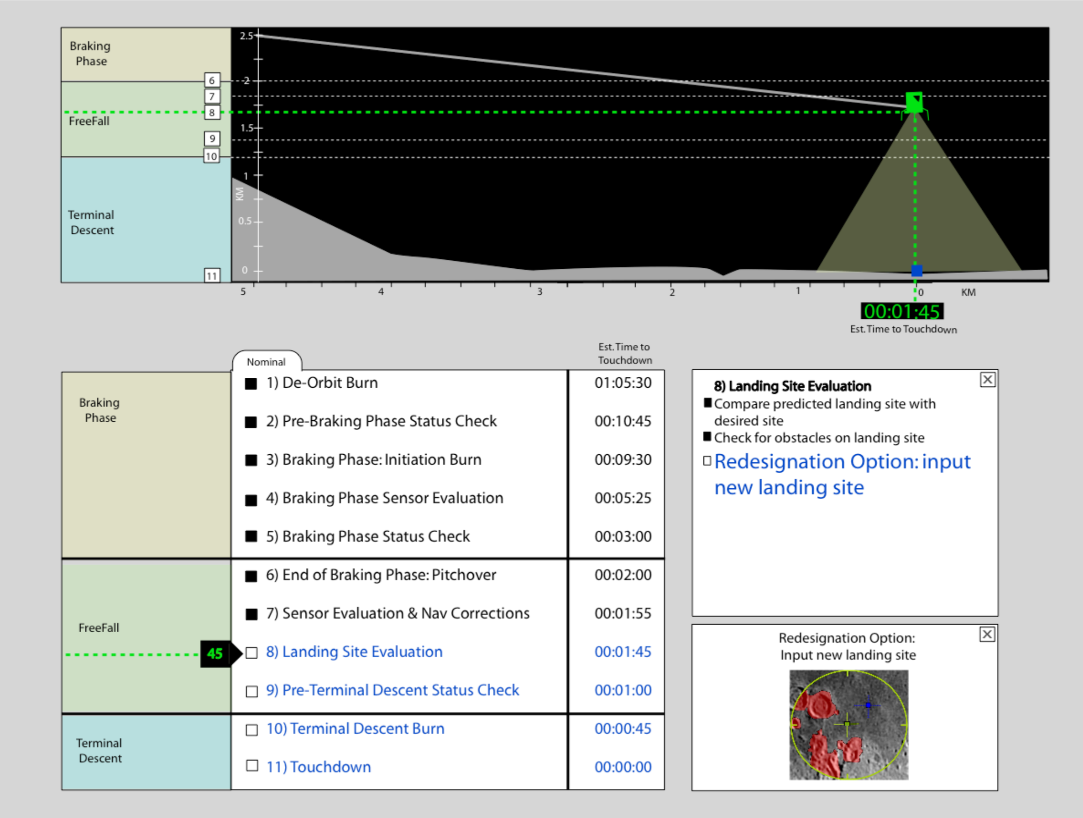
3.4 Situational Awareness (SA) Display

3.4.1 SA Display Introduction

As the name implies, the purpose of the Situational Awareness (SA) Display is to provide the crew with situational awareness, connecting space and time of events during the landing process. Situation awareness is the perception of elements in the current situation, the integration and comprehension of these elements and current situation, and the projection of future status based on comprehension (Endsley, 1995). Maintaining situation awareness while executing a task, particularly when it involves using automation, is important because it promotes safety and permits operators to accurately do their job. When automation is involved, it has been shown that operators could have decreased situation awareness (Endsley, 1996; Parasuraman, 2000; Parasuraman & Riley, 1997) and an inability to maintain mode awareness (Parasuraman & Riley, 1997; Sarter & Woods, 1994). It is thus deemed critical for any human-in-the-loop interface to provide and promote situational awareness.

Previous space shuttle display research has emphasized the need for a comprehensive SA display for both current and future events. The recent Space Shuttle Cockpit Avionics Upgrade (CAU) investigation resulted in advocating a display that included both current and future status (McCandless et al., in press). Having the operator, be it on board or remotely, understand the vehicle's state is critical for trust and for preparedness in case of future emergencies. If operators have good situation awareness, they will be able to project correctly what future states should occur and recognize when deviations from the expected take place.

In general, a LAV SA display should provide the crew with a "big picture" of events and stages occurring during the landing process thus communicating when and where the lunar lander is both currently and predicted future state, and when and how the human is assigned particular responsibilities. This display, while modular, could be shared by the commander and lunar lander pilot as well as any other controllers in the loop. The proposed preliminary LAV SA display (Figure 14) is intended to maintain situation awareness by visualizing the lander in space relative to its current and predicted trajectory, external hazards (terrain), and current and future modes (phases and events) of landing process. Moreover, it keeps the human actively engaged in the sequence of required tasks. The desired results are to enhance safety and mode awareness, and promote timely and accurate interaction with various lander systems as required, particularly when deviations from nominal operations occur.



	Nominal	Est. Time to Touchdown
Braking Phase	■ 1) De-Orbit Burn	01:05:30
	■ 2) Pre-Braking Phase Status Check	00:10:45
	■ 3) Braking Phase: Initiation Burn	00:09:30
	■ 4) Braking Phase Sensor Evaluation	00:05:25
	■ 5) Braking Phase Status Check	00:03:00
FreeFall	■ 6) End of Braking Phase: Pitchover	00:02:00
	■ 7) Sensor Evaluation & Nav Corrections	00:01:55
	☐ 8) Landing Site Evaluation	00:01:45
	☐ 9) Pre-Terminal Descent Status Check	00:01:00
Terminal Descent	☐ 10) Terminal Descent Burn	00:00:45
	☐ 11) Touchdown	00:00:00

8) Landing Site Evaluation
- ■ Compare predicted landing site with desired site
- ■ Check for obstacles on landing site
- ☐ Redesignation Option: input new landing site

Figure 14 Situational Awareness Display

An in-depth analysis of the Apollo landing process was conducted, focusing not only on the astronauts' tasks but also the cognitive requirements (Appendix A Interviews, Conversations, and Meetings, Appendix F Summary of Apollo Press Kits, Appendix G Apollo Landing Sequence Storyboard, and Appendix H Apollo Landing Timeline). One of the artifacts of this analysis was an Apollo landing storyboard and timeline, summarizing the many tasks the astronaut crew had to execute in order to land safely on the Moon (Appendix G Apollo Landing Sequence Storyboard and Appendix H Apollo Landing Timeline). This provided insight as to the number of tasks that had to be done by the crew. For example, due to the limited computing capabilities in Apollo, astronauts had to load specific programs for each of the important phases of the landing sequence. As a result, the Apollo landing process was a well-orchestrated series of events that had to be executed in a timely and accurate fashion.

Future lunar landings, however, will incorporate higher levels of automation, changing the role of the astronauts in the landing process. Instead of initiating programs, which can now be automated, the crew has a larger supervisory monitoring task. As has been demonstrated in numerous studies, as humans are further removed from the control loop, they lose situation awareness (Layton, Smith, & McCoy, 1994; Newman et al., 2005; Parasuraman, Molloy, & Singh, 1993; Parasuraman, Sheridan, & Wickens, 2000) and thus a situational awareness display is needed that correlates the space and time of events. Moreover, because automation feedback is a critical element in maintaining SA, this display should reveal the activities the automation is conducting and when, where, how and why humans should and could intervene. This is critical especially when considering remote operators of the LAV, as they will lack the physical cues an astronaut crew would receive while in the vehicle.

When specifically dealing with the landing on the Moon, much of the Apollo-era documentation refers to vertical profiles of the landing sequence (e.g., Klumpp, 1968; NASA, 1966). Needless to say, the vertical component of landing is an integral part of the landing process – it is a vertical landing on the Moon. Inspired by this documentation and the fact that the human role for the majority of the landing sequence is supervisory we propose an SA display that incorporates a vertical profile view. In addition to providing SA for the crew, this display provides a common operational picture between all humans in the loop, whether it is on the lander or on the earth.

Utilizing a vertical navigation aid to provide situation awareness and timeline information for mode awareness was also suggested by human factors experts at NASA Ames Research Center (Appendix A Interviews, Conversations, and Meetings: Interview 9). This is not surprising if we consider all the published support for trend displays, similar to the proposed vertical SA display (e.g., Atkins et al., 2004; Walton, Quinn, & Atkins, 2002). Woods (1995) demonstrated the importance of trend displays for SA in a space setting in his description of Apollo 13 mishap: a trend display would have saved 54 minutes of trial and error in identifying the cause of the emergency (Woods, 1995). In general, trend displays support human operator monitoring, diagnosis, and control, promoting, in essence, situational awareness (Guerlain, Jamieson, Bullemer, & Blair, 2002).

Furthermore, there are some clear advantages of using a vertical situation awareness display, such as ease in determining distance between lander and other features, including landing site, and ease in discriminating between vertical deviations from trajectory (adapted from SAE, 2001). A vertical trend display is especially important given the uncertainty of both the prior mapping as well as the performance of the LIDAR. Giving the crew the ability to understand how well the LIDAR is performing early in the sequence will prepare them for potential map-tie errors after pitchover. The ability to provide a prediction for a critical future state is a critical component of any technology designed to promote SA.

A horizontal situational awareness display for the LAV (for example, see McCandless et al., 2005) would only be beneficial for large lateral movements such as landing redesignation to sites not near the original landing site (i.e., a large lateral displacement needs to be implemented by the operator). Nonetheless, lateral deviations are not ignored in our display system concept. For the final descent phase, these deviations can be detected in the top-down view of the landing area, presented in the Landing Zone display; the top-down view is analogous to a horizontal situation display. For the initial phases, a horizontal display for lateral displacement is still under investigation.

Based on the cognitive task analysis, the important information relevant to maintaining situation awareness for the task of landing on the Moon is:

- Trajectory (intended, past, and predicted)
- Lander's current state
- Lander capabilities
- Trajectory parameters (or phases)
- Landing site location
- Time to touchdown
- Hazards, obstacles awareness
- Terrain (database information)
- Information transmission (datalink)
- Fuel constraints
- Feedback for any significant deviations from the nominal situation
- Notification of any expected actions expected to be performed by the human

3.4.2 SA Display Design

The Situational Awareness display is divided into three major sections: profile view, events list, and expansion boxes (**Error! Reference source not found.**). Within the profile view, the trajectory of the LAV is depicted as well as the estimated time to landing site. Both the profile view and events list have a timeline of major landing phases. The events lists current (high-level) tasks, while the expansion boxes provide further details about the specific activities done by the automation or the operator.

3.4.2.1 Profile View

The top half of the display is the profile view (Figure 15). Similar to a vertical descent display, this profile view shows the trajectory of the lunar lander as it approaches the landing site. Shown in grey (bottom) is the predicted terrain altitude. The lander icon's orientation matches to the current pitch angle of the lander. In Figure 15, the lander has completed the pitchover maneuver and thus, would have a pitch angle of 0º. Earlier in the landing process, it would be tilted relative to the vertical, indicating a larger pitch angle (see also Figure 17).

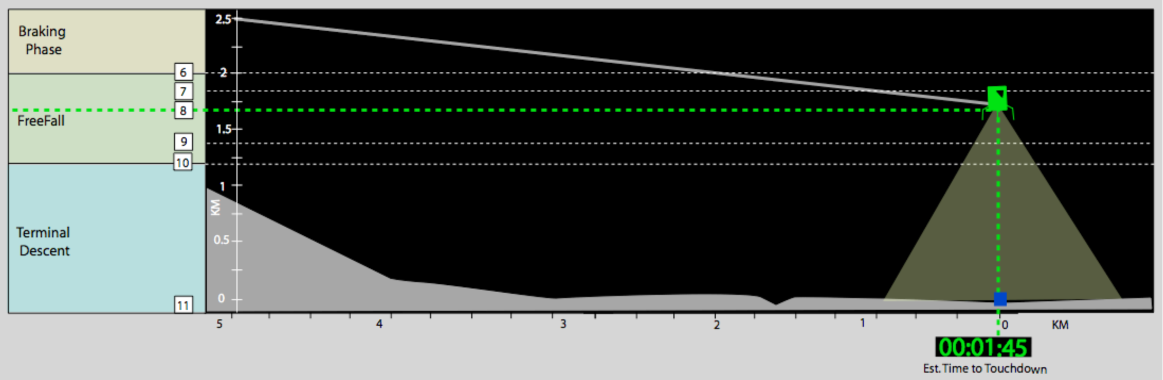


Figure 15 Top Portion of Situational Awareness Display Profile View

It is assumed that there will be a preliminary terrain profile for the planned trajectory (see Appendix C Lunar Terrain Altitude Mapping: Past, Present, and Future Data; Section 3.1 H-SI Design Assumptions). If there are any terrain deviations from the expected based on sensor information, mainly LIDAR updates, these updates would be marked on the actual terrain profile.

The trajectory is plotted against altitude and distance to the landing site. Both of these axes are linear, yet as the trajectory progresses, the scales change because the display should always be focused on the current landing phase (essentially, a zooming feature). For example, it is not as imperative to show the last kilometer of the trajectory when in the beginning of the braking phase; the operator will be more interested in knowing they are at the correct altitude. While there is no axis of time, there is an estimated time to touchdown below the lander icon. This countdown is the same as the one located in the System Status (SS) display. From an SA perspective, it is critical to know where you are in time. Since it is deemed as one of the critical variables during the landing process, it is repeated in the SA display (Appendix G Apollo Landing Sequence Storyboard and Appendix E Decision Ladders).

Highlighted in Figure 15 are the landing phases in "timeline" format: braking, freefall, and terminal descent. This "timeline" does not directly depict time (as there is no time axis), but it relates the position of the lander to phase of the landing process. Embedded within this "timeline" is a series of numbers that match the event numbers checklist (Figure 14). The numbered events are mapped in time to a checklist of critical events executed by humans and/or automation, while in the profile view, these same events are mapped in space. In Figure 15, the lander happens to be in the freefall phase, specifically executing event number 8. If the crew "scrolled over" a numbered event in the profile view, the estimated time to touchdown from this event would pop up (Figure 16).

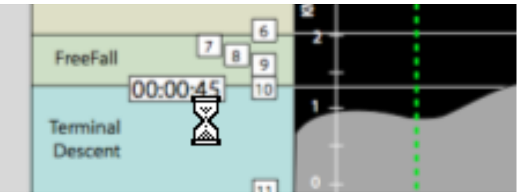


Figure 16 "Scroll Over" of Event with ETT

The current location in time and place of the lander is depicted in green dashed lines. Furthermore, the lander is green to match the lander icon in the LZ display. The future portion of the trajectory is depicted in blue (in Figure 15) the future trajectory is not visible as it is below the current position line; see Figure 17 for projected trajectory example). The destined landing site is also colored blue, which represents future states. The portion of the trajectory that has already passed is shown in grey. Blue also happens to be used for landing site redesignation in the LZ display. These color selections were driven by the LZ display and are still in development.

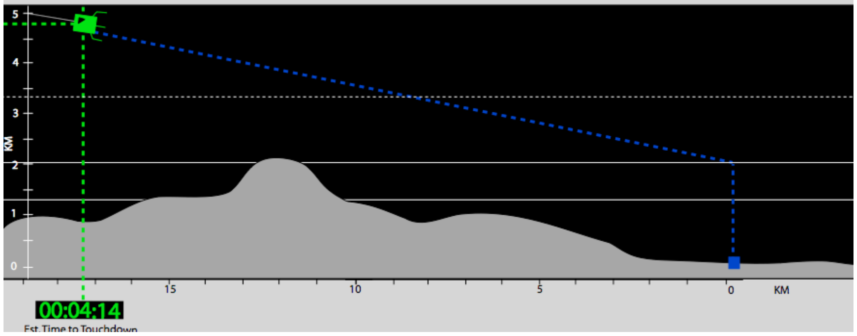


Figure 17 Close up of Profile View, Projected Trajectory

As seen in Figure 15, there are other horizontal lines on the profile view. The solid lines indicate when a landing phase changes, for example, from Braking Phase to Freefall. The dashed lines are connected to the numbered events, further highlighting events to space, i.e., the position of the lander. It is acknowledged that it is possible for clutter to occur when too many events are clustered together; this is solved when the profile view is enlarged through a zoom function.

Only once the Braking Phase ends, does the display show the LIDAR's beam area (Figure 18. While the LIDAR is always on during the landing process, it only "sees" the landing site after pitchover. Thus it is important for the crew to visualize the beam area because it is one of the primary sources of sensor information that has a direct impact on landing site redesignation, a critical crew task.

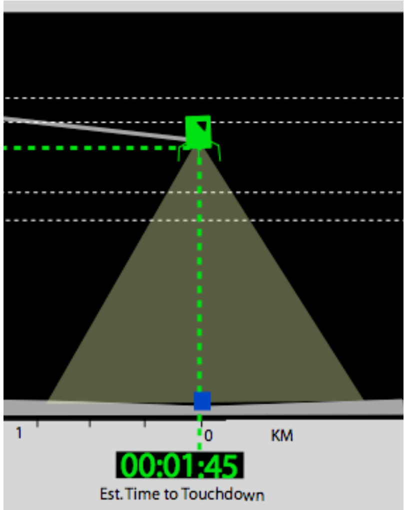


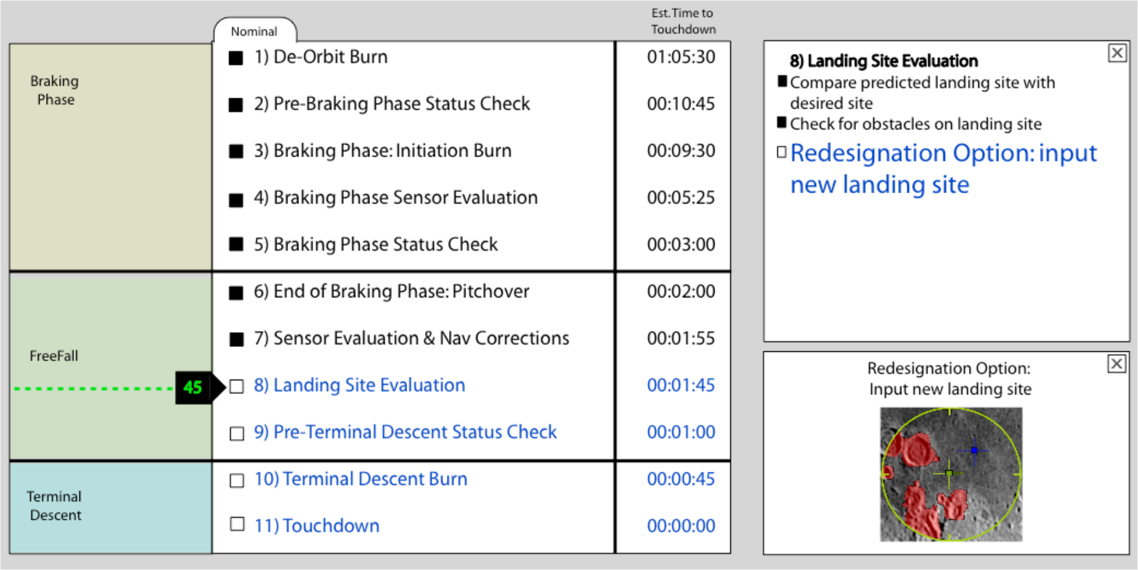
Figure 18 Zoom of LIDAR Beam Representation in SA Display

In summary, the information provided in the profile view (top half of SA display):

- Lander altitude and downrange from landing site
- Estimated time to touchdown
- Terrain altitude
- Graphical representation of LIDAR beam area and lander's pitch angle
- Current location in space and time
- Current landing phase and event
- Relative information (space and time) about other phases and events

3.4.2.2 Event List

The bottom half of the SA display includes the event list and two expansion boxes (Figure 19). Two boxes (instead of one) were selected because three levels of hierarchical information were identified: high level (events list), list of activities within an event, and finally, potential details about a specific activity. On the left, the event list is similar to a checklist; the main difference is the event list is not an enumeration of tasks to be *done*, but rather major events in the landing process that occur. A set of eleven events are shown; however, it is worth noting that this list is based on the major events that occurred during an Apollo landing sequence, adapted to accommodate the new Draper trajectories. Each event is numbered and thus, cross-referenced in the profile view. This was done to facilitate cognitive matching between the events list and the profile view.



Nominal	Est. Time to Touchdown
■ 1) De-Orbit Burn	01:05:30
■ 2) Pre-Braking Phase Status Check	00:10:45
■ 3) Braking Phase: Initiation Burn	00:09:30
■ 4) Braking Phase Sensor Evaluation	00:05:25
■ 5) Braking Phase Status Check	00:03:00
■ 6) End of Braking Phase: Pitchover	00:02:00
■ 7) Sensor Evaluation & Nav Corrections	00:01:55
☐ 8) Landing Site Evaluation	00:01:45
☐ 9) Pre-Terminal Descent Status Check	00:01:00
☐ 10) Terminal Descent Burn	00:00:45
☐ 11) Touchdown	00:00:00

8) Landing Site Evaluation
- ■ Compare predicted landing site with desired site
- ■ Check for obstacles on landing site
- ☐ Redesignation Option: input new landing site

Redesignation Option:
Input new landing site

Figure 19 Event List and Expansion Boxes

Once an event is completed, it changes colors to black and its corresponding check box is darkened. Future events are in blue text. The current event is highlighted with a green dashed line and an arrow box. The dashed line, similar to the one in the profile view, is within the trajectory phase. The arrow box has a timer, indicating the remaining time until the event finishes; this was deemed crucial because during Apollo, events had to be executed in a very precise and timely manner, and though automation manages most of these events and activities, time is still of the essence. In Figure 19, the current event is "Landing Site Evaluation", within the FreeFall Phase, and there are 45 seconds remaining in this event.

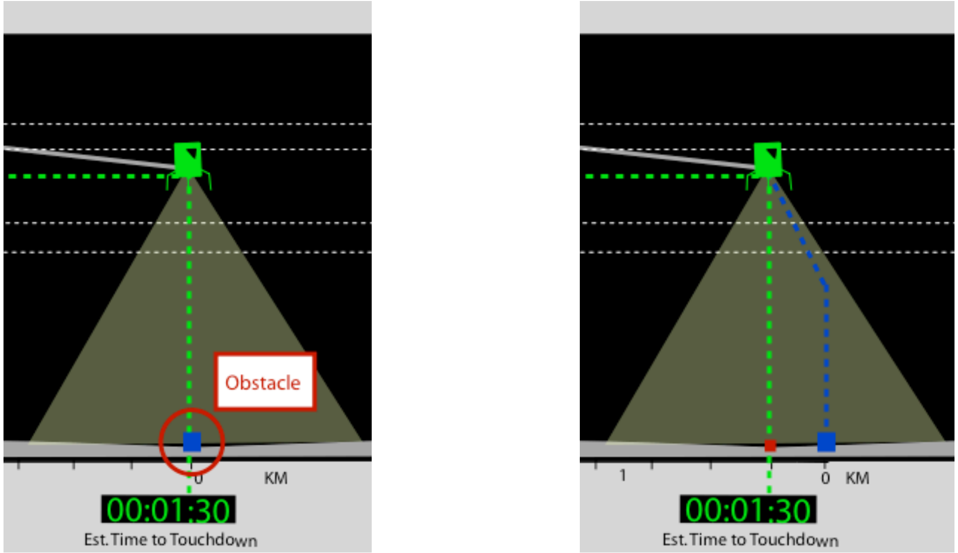
To the right of every event, there is a time stamp, which is the estimated time to the start of each event. This time should be calculated based on the current state and trajectory. If a change or update in the trajectory occurred, the time stamps would be refreshed, reflecting the new estimated times base on the current position and trajectory.

3.4.2.3 Expansion Boxes

To the right of the event list, there are two expansion boxes. If the crew would like to see what specific activities were taking place during an event, the event in the list can be selected and the top expansion box would contain an activities list. Most of these activities would be automated but would be highlighted if human intervention was required. While the majority of tasks are expected to be automated, it is expected that some procedures will require human interaction. Future improvements will include improving the saliency of the activity and correspondence with SS display's functional allocation (see 3.4.3 for more explanation). The second expansion box further expands an activity to show lower level detail if needed.

3.4.2.4 Human Intervention Example: Redesignation of Landing Site

The Situational Awareness display focuses on integrating space and time information during the landing process, under nominal and off-nominal circumstances. One example of an off-nominal circumstance is the detection of an obstacle. Assuming that the detection was automated (e.g., LIDAR sensed a new hazard), this new information would be shown in the SA display as it affects the trajectory (Figure 20). Once the crew determines a new landing site (shown in blue, obstacle in red), a new trajectory, calculated and implemented by the GN & C, is shown in the profile view. Thus the LZ and SA displays would be integrated, showing changes on both in real-time.



a) Close up of Obstacle Detection **b) Close up of Landing Site Redesignation**

Figure 20 Situational Awareness Display Details

3.4.2.5 Alternate Design Proposals

Throughout the design process, there have been several major design changes to the SA display. These will subsequently be described, including reasons for the alterations. The changes were implemented based on the many conversations, interviews, and peer-review sessions held during the design process.

In its original inception, the SA display included the top-down view of the landing site with the vertical profile. While there were some improvements to cognitively match these displays that had different points of view (Appendix A Interviews, Conversations, and Meetings: 8), it was soon determined that the top-down view was more closely related to the LZ display, where it now resides.

A time axis was once part of the profile view below the downrange axis. Since the forward velocity of the lander is not constant (decelerating towards the landing site), one of the two axes (time or distance) had to be non-linear. Common practice dictates to make the distance linear and the time, non-linear. This would prevent a static axis in time for the profile view, which we hypothesize would be difficult for the user to understand. We prioritized space and time, and concluded that space was more important, hence it was kept as the major axis, and time is shown in other manners (specifically, in the Event List).

One of our major sources of information used to understand the cognitive demands on the Apollo crew was the “Apollo Lunar Surface Journal” (Jones, 2000). The voice transcripts were critical in this respect, and inspired the vision of a digitized version of this for use in the landing process. The information datalink would provide the LAV operator a written history of all the conversations and textual information that was communicated between ground controllers and the others, such as a “command module” crew. A datalink is already in existence in aircraft and military operations, and this idea was incorporated into the SA display. It would digitize (and transcribe) all the voice transmissions between the crew, ground control (be it Earth or Moon), and the equivalent to a Command Module (likely, Crew Exploration Vehicle); it would also permit text inputs. It was eliminated in our design by an external review process, and this change gave space for two expansion boxes that our current design includes.

The most important change imposed by recently updated trajectory information occurred on the profile view. Originally, the Apollo trajectory phases were mapped horizontally, as the path was curvilinear (NASA, 1966). The Draper trajectories phases have the vertical as a more important component, greatly decreasing the time spent pitching over; many of the events occur over the landing site (a single point in the horizontal axis). The phases had to be placed vertically alongside the profile view in order to visualize them and avoid clutter. Furthermore, only the most important events, such as phase changes, could be highlighted in the vertical in order to prevent obstruction of other display elements.

3.4.3 Future SA Display Issues

There are issues that still need to be improved upon within the SA display, and are subsequently discussed in this section.

- The relationship between the vertical SA display and a horizontal SA display. A lateral error track display has not yet been integrated and this will mean that separate displays for vertical and horizontal views require the operator to integrate information across the SA and LZ displays, respectively. 3D displays can be investigated that transition seamlessly from horizontal to vertical but given the current time constraints of this project, this is not an option for at least another year.
- Trajectory Updates. The guidance, navigation, and control systems will continuously be updating the trajectory in real-time. Thus, the profile view of the trajectory should be refreshed every time the GN & C changes the trajectory. The crew, in order to maintain awareness, should be made aware of the changes and be informed of what the automation is doing. Furthermore, these changes affect the estimated times for touchdown. Should the display show every past trajectory change, just the previous one, or, in order to avoid clutter, just the current trajectory? The current design only depicts the new trajectory.

- Emergencies/Aborts. It has not been determined yet what information is most important within the SA display during an abort scenario. It is clear though that trajectory to landing site and nominal event lists is not essential during emergent situations. More likely, the SA display will show an abort checklist and abort opportunity windows visualization, with an emphasis on timing and location. This analysis has yet to be completed because there has been very limited information about abort criteria and scenarios.
- Display consistency. The human-automation allocation of activities should be consistent with the SS display. The SS display distinguishes between purely manual, purely automated, and possibly mixed control of an activity. This aspect will be incorporated in the SA display in the near future.
- Checklists/Procedures. Up to now, a list of events and checklists have been put forward based on Apollo-era documentations and trajectories, adapted to include the new Draper Lunar Access trajectories and components, such as LIDAR. Realistic checklists for the phases should be developed, but this requires a LAV simulator or model. Based on these, it can be more accurately determined what exactly the operators need to see under nominal and abort situations. These checklists are important for both the SA and SS displays.

3.5 System Status (SS) Display

3.5.1 Introduction

The many systems that needed monitoring in the Apollo missions were scattered around the Lunar Module as is seen in the pictures of the Lunar Module (Figure 3), but were critical to making the decision to abort and return to its orbit or to proceed with the mission. The crew had to prioritize the information for the different phases of the flight and had to know where to find the specific information in case of emergencies. The objective of this proposed system status display is to provide crew with immediate and prioritized health and status information, in addition to procedures/checklists in the occurrence of an event that requires intervention. To decrease the workload of the pilot/controller, automation is used to assist in monitoring the system status. Instead of displaying all information at the same time, the system status display only provides the information the pilot needs or requests. A second objective is to provide the crew with a reconfigurable space for systems management when nothing is happening that requires attention.

3.5.2 Motivation and Background Research

As part of the conduct of the cognitive task analysis, it was determined that the Lunar Module Pilot's role in the landing sequence was to monitor all relevant aspects of the LM systems' status (Appendix F: Summary of Apollo Press Kits), (Jones, 2000). This lead to the concept of the System Status (SS) display, designed for efficient cooperation between the person responsible for monitoring health and status information[2] and the automation. Archival Apollo research suggests that monitoring personnel must have access to a wide range of information (displayed by a multitude of gauges and meters in Apollo). From this research, a list was generated of the information requirements that the LMP could at one point wish to examine (Appendix D Preliminary System Status Information Requirements), (NASA, 1969b, 1969c).

The main challenge of the SS display was therefore to display all necessary information in a much smaller area, while avoiding clutter. This display allocation problem was solved through layering. The various information requirements were grouped in categories that make browsing intuitive and efficient. Integration of automation and human control in systems management through visualization was a central focus to both promote rapid and accurate decision making under time pressure as well as provide for high situational awareness of function allocation. The following sections will discuss the workings and purposes of each section of the display in greater detail.

3.5.3 SS Display Design

The SS display, see Figure 21, consists of three primary components: 1) Status alert panel, 2) Procedure panel, and 3) Time panel. The status alert panel and the time panel are fixed modules because they represent critical information items that always need to be seen or are access points for lower level information. The procedure panel is a reconfigurable module which changes according to the information the LMP requests or needs in case of an event that requires intervention. See Appendix B Display Screen Shots: System Status Display; System Status Display for detailed SS display screenshots.

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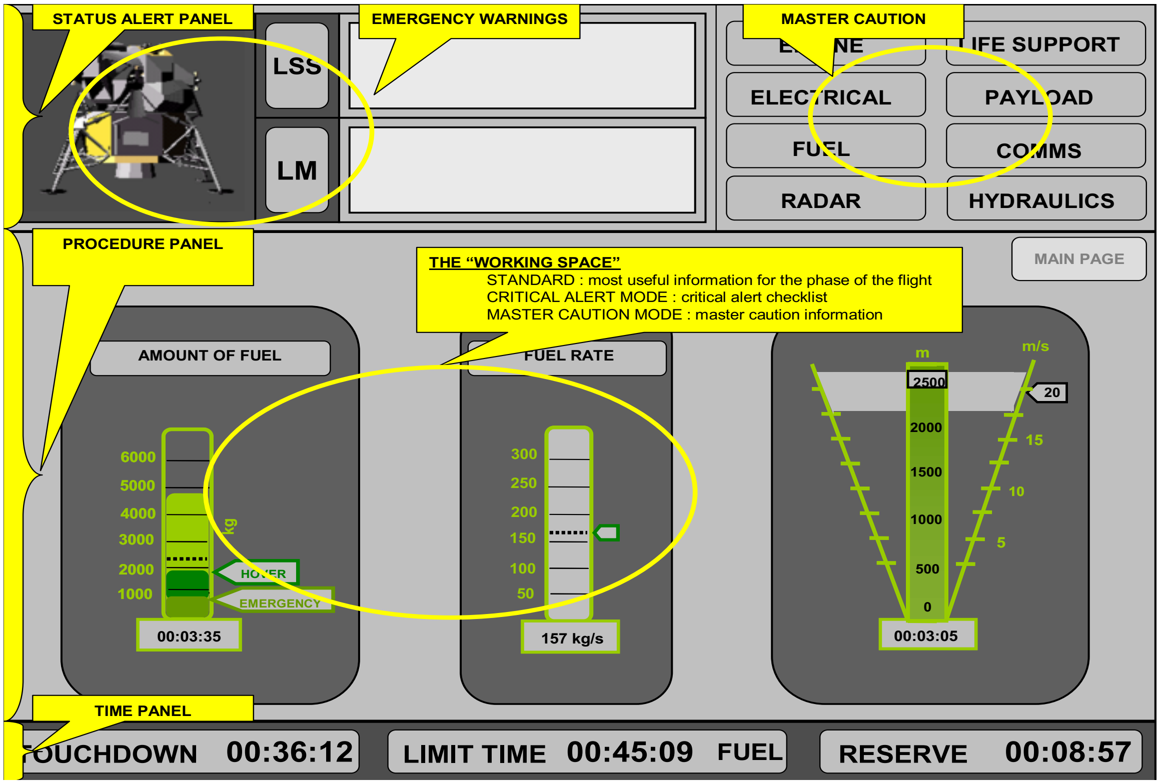
[2] Since this position for the Lunar Access Vehicle is yet labeled, we will refer to the person monitoring health and status information as the LMP, understanding that in the LAV, this person may have a different title or may not even exist.



THE "WORKING SPACE"
STANDARD : most useful information for the phase of the flight
CRITICAL ALERT MODE : critical alert checklist
MASTER CAUTION MODE : master caution information

Figure 21 System Status Main Display

3.5.3.1 Status Alert Panel (SAP)

In case of an emergency or a certain matter that require the attention of the pilot, warning and caution alerts appear in this part of the display (Figure 22). Because the warning and alerting functions of the status alert panel make it the most important panel of the SS display, the panel is located at the top of the display. The use of pictorial warning and alert panels are well-established aircraft cockpit interface design techniques (Stokes, 1988) and additional related research has been underway in the space vehicle community (McCandless et al., in press). The need for these types of displays was also highlighted in several interviews (Appendix A Interviews, Conversations, and Meetings: 1 and 9).

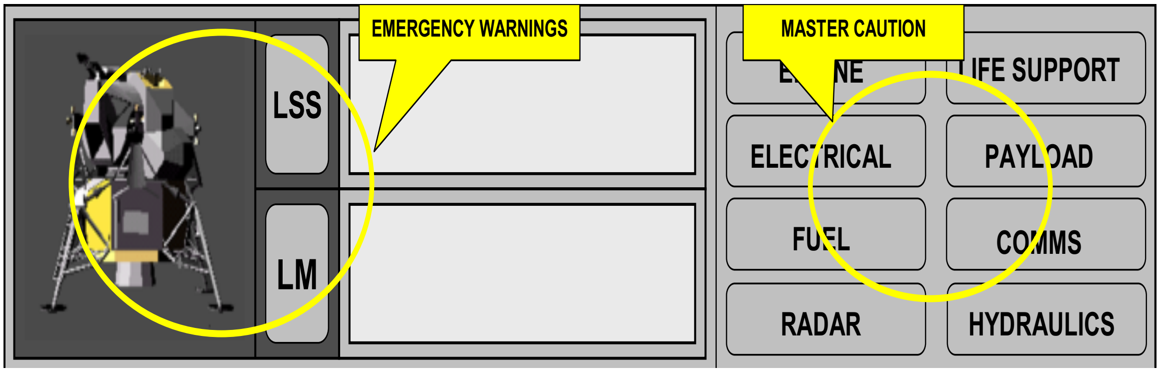


Figure 22 Status Alert Panel

The left part of the SAP is for emergency warnings. The emergency warnings are divided into emergency warnings concerning the Life Support System (LSS) and emergency warnings concerning the lunar module. An emergency warning means a life/systems threatening situation exists that needs attention. The buttons will flash red and in the box adjacent to the emergency warning, the nature of the warning will be displayed. When an emergency warning occurs concerning the lunar module, the failing system will also flash red in the lunar module overview picture. By pressing the emergency warning buttons, the necessary information or procedure checklist will appear in the working space of the procedure panel.

The master caution buttons are located on the right side of the upper section of the SAP, and turn yellow when the pilot needs to be aware of a changing situation or in case of a non-life threatening emergency. If the subsystem is part of a major emergency, the buttons will turn red. In this case, by pressing the button, the information requested will appear in the working space. The master caution buttons currently depicted only represent the presumed major subsystems of the LAV (NASA, 1969a, 1969b) and are only placeholders until more detail is known about the actual vehicle. The goal is to create caution buttons that will point to the root of the problem, allowing the crew to focus quickly on the source of the malfunction (McCandless, McCann, & Hilty, 2003).

3.5.3.2 Procedure Panel

The procedure panel (PP) (Figure 23), is a reconfigurable module, unlike the SAP which remains fixed and unchangeable. The PP consists of a working space, which is a space where relevant or desired information is displayed. The PP also includes a main page button, which is not selectable until lower display levels are accessed. Nominally the working space displays information/instruments for the relevant stage of descent. The "working space" has three modes. The standard mode, the critical alert mode, and the master caution mode. The standard mode displays the most useful information for the phase of flight. The critical alert mode displays the critical alert checklists in case of an emergency warning and the checklist design will be discussed in a subsequent paragraph. The master caution mode displays relevant information when a master caution button is selected. These modes provide immediate and prioritized health and status information of subsystems or checklists.

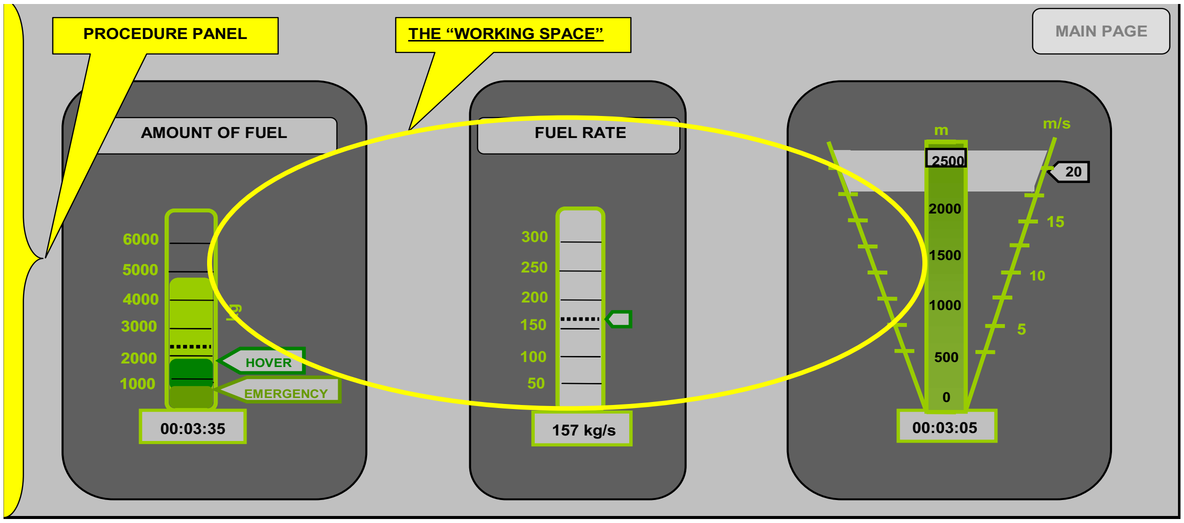
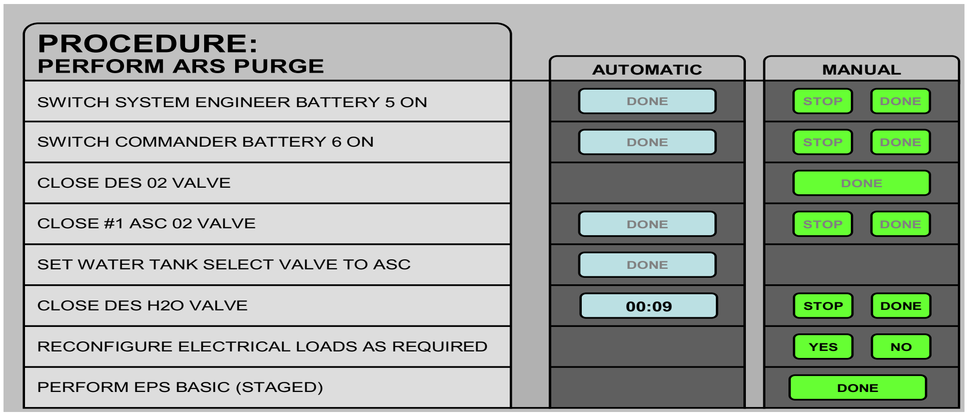


Figure 23 Procedure Panel

3.5.3.3 Checklist Design

In the occurrence of an emergent or urgent event that requires intervention, a procedure or checklist will appear in the working space (Figure 24). A checklist informs the pilot what to do, how to do it, when to do it, and provides feedback as to the status of the procedure. In addition to the actual checklist items, the crew is also given direct information as to who has responsibility for a particular item (the automation or the human), and also whether or not the automation can be overridden by the crew. This clear and unambiguous role allocation is required to prevent mode confusion which is a serious problem for highly automated systems (Parasuraman, & Riley, 1997; Parasuraman, Sheridan, & Wickens, 2000; Sheridan, 2002; Wickens & Hollands, 2000)



PROCEDURE:
PERFORM ARS PURGE

	AUTOMATIC	MANUAL
SWITCH SYSTEM ENGINEER BATTERY 5 ON	DONE	STOP DONE
SWITCH COMMANDER BATTERY 6 ON	DONE	STOP DONE
CLOSE DES 02 VALVE		DONE
CLOSE #1 ASC 02 VALVE	DONE	STOP DONE
SET WATER TANK SELECT VALVE TO ASC	DONE	
CLOSE DES H2O VALVE	00:09	STOP DONE
RECONFIGURE ELECTRICAL LOADS AS REQUIRED		YES NO
PERFORM EPS BASIC (STAGED)		DONE

Figure 24 Checklist with Role Allocations

As discussed, each individual task in the checklist can be allocated to the automation or to the human exclusively, or operators can elect to take control from the automation if desired. The allocation of the task is made clear in the checklist. When the task is allocated to the human only, for example when the crew has to decide whether or not to abort, the human simple presses the button “done” when finished (Figure 25).

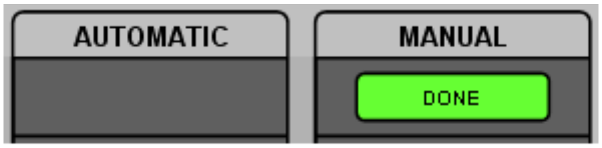


Figure 25 Human Allocation

When the task is allocated to the automation only, the checklist provides information to the human about the status of the task with the buttons in Figure 26. When the automation is responsible for a task and begins the task, “in progress” is displayed and when the task is complete, the button shows “done” and turns gray.

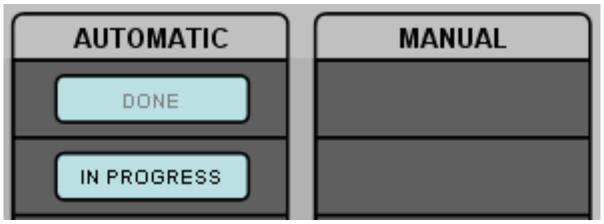


Figure 26 Automation Allocation

When the task is allocated to the automation, but the human can intervene if desired (known as management-by-exception), the checklist item will look like Figure 27. The automation will perform the task when the counter stops. The human can decide to intervene by pressing the stop button. Then the human has to press the “done” button after executing the task.

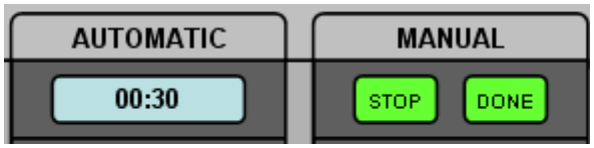


Figure 27 Shared Human-Computer Allocation

3.5.3.4 Time Panel

The time panel is a fixed module and displays three estimated times. The first is “touchdown”; this is the estimated time to touchdown. The second is the estimated “limit time” with the indication of the limit factor. In Figure 28, this limiting factor is fuel, but could be factors like oxygen or factors concerning specific payload. The third entry is “reserve”; this is the estimated reserve time which is the difference between the actual estimated time to touchdown and the theoretical available time. The estimated reserve time should always be positive.

Figure 28 Time Panel

3.5.4 System Status Display Future Issues

The SS display design described is a preliminary outline of the actual interface. The content of the different panels need more consideration. Major areas for future investigation include:

- The master caution panel.
    - The master caution buttons are now a representation of the subsystems. In future designs we need to know which subsystems the LAV has, which subsystems must have a master caution button and if other information outside of the subsystems needs an alert.
    - What information will be provided to the crew after pressing a master caution button? Related questions include how should lower level functions be allocated between humans and automation, and how do the subsystems work and what information concerning the subsystem does the crew need to know? Is the information always the same after accessing the subsystem master caution or does the information change according to the situation the lunar module is in?
- The second issue concerns the procedure panel. The working space has only three modes now; the standard mode, the critical alert mode and the master caution mode. Future research should focus on making the standard mode also reconfigurable.
    - In addition, it is not clear how the automation would select the most useful information for the relevant phase of flight, as well as how the crew could request other information or the synthesis of related information.
    - What sensors need to have "virtual" instruments and what integrated displays could be developed from multiple sensor data? Previous problems on Apollo missions underscore the need for integrated displays (Woods, 1995) but until the LAV is actually designed, it is impossible to develop accurate integrated displays.
- The third issue concerns the development of a navigation bar that makes the reconfigurable mode easier to navigate. This navigation bar will allow navigation to any display. This issue has been raised previously in shuttle display design (McCandless, McCann, & Hilty, 2003). In the procedure panel, at the top of the panel, a navigation bar could be implemented, much like the "main page" button. The navigation bar will consist of several buttons that will access the information requested for by the pilot.

4 Overall Design Issues and Next Steps

4.1 Overall Design Issues

The incomplete sensor survey, unknown system configuration, and limited trajectory information are the greatest impediments for further development of specific H-SI elements, and also the functional requirement development. The system configuration and crew position can significantly affect the number of displays, the size of display and the placement of displays, not to mention all the individual display elements. In order to make necessary modifications to current H-SI design, we must obtain more design specifications about lunar lander vehicle as well as senor and trajectory data from other Lunar Assess teams.

This HS-I prototype is designed for crew either in or remotely controlling a lunar lander vehicle, not an aircraft or a space shuttle. Astronauts in the LAV are expected to engage in primarily supervisory control, with manual control intervention in the final vertical stages of flight and only in cases of system problems. Thus many displays in use in other air and spacecraft are not relevant. Finally, these design concepts are preliminary and will undergo continual refinement both for the initial demonstration development, as well as in later years.

4.2 Next Steps

We will continue to improve the conceptual prototype of H-SI by conducting various peer reviews and design critiques, but our focus is shifting from conceptual design to functional design. The following list contains major tasks we are going to complete in the next design phase.

- Modular for integration
- Develop scenarios for demonstration
- Start programming work for the dynamic demonstration of H-SI prototype
- Conduct usability evaluations for current H-SI prototype
- Work on unsolved and new research issues
  - Braking view
  - Mode confusion and control authority evaluations
  - Design on-screen smart checklist (concept only, not actual checklist)
  - Abort criteria and decision-making support
  - Vertical vs. horizontal SA displays

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Appendix A Interviews, Conversations, and Meetings

This appendix includes a summary or a link to interviews, conversations and/or meetings conducted under the cognitive task analysis for the Lunar Access Project.

During the course of three months, fourteen interviews or meetings were held, four of which were Apollo astronauts. Among the interviews were engineers that worked on the Apollo lunar lander and NASA experts from three centers, NASA Ames, NASA Johnson, and JPL. Furthermore, there was a site visit to two of the subcontractors within the Lunar Access team. This information was captured as either a downloadable wav file or a summary listed below. All the interviews or meetings are organized in flowing order.

1) Prof. Barrett Caldwell, Purdue University
2) Harrison "Jack" Schmitt, PhD, Apollo 17 Lunar Module Pilot
3) Gordon Fullerton, Apollo ground controller and Space Shuttle astronaut
4) Allan Klumpp, PhD, Apollo Guidance Computer Engineer
5) Honeywell Meeting
6) NASA Johnson Space Center Meeting
7) Mr. Steve Paschall II, Draper Laboratory
8) Mary Kaiser, PhD, NASA Ames Research Center
9) Miwa Hayashi, PhD, and Robert McCann, PhD, NASA Ames Research Center
10) Captain John Young, Apollo 16 Commander and Space Shuttle Astronaut
11) Dr. Gary Spiers, NASA Jet Propulsion Laboratory
12) AV-8B Harrier and MV-22 Osprey Simulators
13) Buzz Aldrin, Apollo 11 Lunar Module Pilot
14) Mr. Steve Paschall II, Draper Laboratory

1) Prof. Barrett Caldwell, Purdue University
Date: June 3, 2005
Duration: 1 hour
Conducted by: Jessica Marquez

Prof. Caldwell's expertise lies in information technology and human factors engineering. In particular, he has investigated communication within space mission control rooms, specifically related to shuttle and International Space Station.

Summary Highlights:

- Mission control at JSC: different types of communication (voice, telemetry, mission profile, procedures). There is no unified communication visualization.
- When dealing with ISS – the mission and the crews remain on board for long periods of time. In this case, the spacecraft (ISS) changes – the state of the system changes – which are not communicated to ground. Thus the expertise now shifts from ground control to crew.
- Need for knowledge synchronization between mission control and crew.

- Levels of Automation: must allow for a sliding scale of automation and to see what the local automation is doing, when it is doing it.
- Time scales of problems: tasks that need to be dealt with in a 5 second time frame should be automated. Beyond that (30 seconds, 5 minutes), humans should prioritize. 30 minutes – this is something mission control deals with.
- Mission control displays:
    - Mostly shows aged status and not state
    - Status == this is how a sensor reads
    - State == this is how the system is behaving
    - Future displays should incorporate both
- Future displays: considering process control line and timeline (for future states).

2) Harrison “Jack” Schmitt, PhD, Apollo 17 Lunar Module Pilot

Date: June 17, 2005
Duration: 1 hour
Conducted by: Cristin Smith and Jessica Marquez

Download wav file: http://web.mit.edu/aeroastro/www/labs/halab/lunar.html

A list of the questions prepared beforehand for Jack Schmitt is listed below. Some of the questions may not have been touched on due to time constraints.

1) Could you please explain your experience on the Apollo 17 landing in terms of the things that stand out as having been unique to your mission?
2) When were you first able to see the landing site? Were you able/allowed to see it at all? At that point, were you able to see the landing site well enough to distinguish obstacles and determine if the LS must be redesignated?
3) Approximately how much time did you have to redesignate the LS?
4) Did it feel rushed?
5) Could you have done a better landing if you had had more time and earlier visibility of the LS?
6) How beneficial would it be to have the ability to see the LS earlier in the landing sequence?
7) What did the landing feel like? Did it feel like you were moving towards the Moon fast? Slowly?
8) What things could you sense and/or see? Rate?
9) Did the geometry and size of the window constrain the footprint of possible landing sites that you could redesignate to? Give you a frame of reference?
10) Would you have liked to have seen more? For personal reasons or performance reasons?
11) With respect to the use of “nouns” and “verbs” for communicating commands, did you feel that this was a good/efficient way to communicate the information and input information?
12) I assume you had to just memorize these numbers and their meanings. Is this correct?
13) Is there some way that you have thought would have been more efficient or better to do the same tasks?
14) I know that you were primarily responsible for monitoring the health of the vehicle, updating the AGS, and communicating information to the Commander during the landing phase. I noticed that you had several different methods for determining the same piece of information (altitude, position, etc). Was there ever a mismatch in this information or a sensor mismatch? What was the protocol to handle such a mismatch?
15) Did you feel that you had too much information in front of you at times? Did you ever feel like you wanted more? In other words, did you always feel “in-the-loop” in terms of always knowing what was going on in your vehicle without having to deduce that information yourself?
16) What do you feel was the value of having an astronaut designate the landing site?

17) What do you see as the role of humans in the next lunar landing?
18) Could you please explain landing abort to us? What were the conditions for abort? Who made the decision? What was your window to abort and when and to where?
19) What do you envision the next generation lunar lander display looking like? What key technologies will be incorporated into the display?

3) Gordon Fullerton, Apollo Ground Controller and Space Shuttle Astronaut

Date: June 22, 2005
Duration: 1 hour
Conducted by: Cristin Smith

Gordon Fullerton was the CapCom ground controller for Apollo 17. He later joined the Shuttle program and flew as Pilot on the third Shuttle mission (STS-3) He also commanded the 19th Shuttle flight, STS-51F

Summary:

- LM computer displays were pure numbers
- 5, 5-digit registers and 2, 2-digit registers
- Did they astronauts like/dislike/have any feelings toward the use of nouns and verbs for commands?
    - Had to memorize what the nouns and verbs were and the corresponding numbers
    - Verbs = actions and required input
    - "Did they like it? They accepted it, they learned. They were going to the Moon, what'd they care?"
- Who made the abort decision?
    - "the one advantage the ground had was having a whole room full of people so they could watch all the telemetry constantly – more than the crew could watch"
    - LCD screens didn't exist to show a lot of numbers.
        - Just lights that went on and off that meant certain things OR
        - Mechanical movements
- Do you believe there's a benefit to providing the information that only the ground had during Apollo?
    - "put smarts into the displays so that if you had to do it again you can digest the data at the decision level"
    - There are a whole lot of parameters that are being checked on the ground though
    - Nothing works like you want it to the first time
    - Apollo 11 1201 alarm – the ground made the call on that
- What was ground control's role in the redesignation of a landing site?
    - Not sure if the ground had real-time TV feed
    - Only voice data, so really no role
- Was the role of the ground primarily a second set of eyes?
    - It takes more than 2 guys to watch and act if something went wrong, in a timely manner
    - Skylab was the same way – lots of people on the ground in the back room
    - But for shuttle, the assumption was that it would fly every 2 weeks, so they couldn't afford such a large ground crew.
    - Wanted to automate almost all of it

  - They figured the crew will have flight management software on orbit and anything you needed to know will be programmed in there.
  - Make everything redundant
  - What about an accelerometer that is a bad guy and starts building up a bias, but look ok. It's always going to be a little off – how much is ok? What do you do with it? Turn it off forever, etc? It's impossible to program all of this logic, especially to the degree that the people who work with them everyday understand → human value
  - The shuttle never came close to the nonsense about fully automating it. Never made it all on-board and self-contained like they had planned → still a large ground crew
- You touched on this issue of a sensor mismatch. What do you believe is the human's role in that if any?
  - It take s a human to make that decision…they know their system much better than the automation
  - Whenever something went wrong, there was always a waterfall of messages…needs to cut this down and get to the root of the problem.

4) Allan Klumpp, PhD, Apollo Guidance Computer Engineer
Date: June 23, 2005
Duration: 2 hours
Conducted by: Cristin Smith and Jessica Marquez

Download wav file: http://web.mit.edu/aeroastro/www/labs/halab/lunar.html

Allan Klumpp, PhD, worked at Draper Laboratories (then known as the MIT Instrumentation Laboratory) during the Apollo program. He was one of the principle designers of the Apollo guidance computer, specifically in charge of the Apollo lunar descent phase.

5) Honeywell Meeting
Date: June 28, 2005
Duration: 4 hours
Conducted by: Cristin Smith

Summary:

- Profile view requires a cognitive rotation, which is mentally consuming and slow with errors
- Look at NASA requirements for operator interface/control
- Grid lines
    - Contoured grid lines
    - Some customers like them, some hate them
- Look into millimeter wave radar EV, pulse-doplars (Navy?)
- Fusion of EV and database mapping
    - John Raising at AFRL
- "no fly zone" box showing vertical and horizontal "Berkshire" signs
    - Make things in such a way that they're very natural
    - Affordance
    - Put as much good info into one display as opposed to separate displays
- Include timeline with profile view
    - Make it very natural
    - Maybe move events over as they pass
- "pathway in the sky"
    - Rectangles that you fly through
    - Pros and Cons
    - Can lead to cognitive tunneling (too focused on the mission, loose sight/awareness of surroundings) – could also be an artifact of the testing
- PFD = Pilot Flight Design
- Control devices
    - Perhaps talk to SR71 pilots…what were they wearing? Gloves?
    - Common Controller
        - Buttons on top that allow user to switch through difference displays
        - Roll ball to move cursor on the side of the controller
        - Would need to be scaled to use with a big glove
    - HOTACS
    - What were the vibrations like during a Lunar landing – question for a astronauts
    - A lot of times you get "POGO" from rocket engines (especially throttle-able ones)
    - Good to consider vibration effects
- Allowing crew to see behind them...be able to slew display to see behind the vehicle?
- Virtual cockpit…may be a reality by time we return to the Moon
- Perhaps instead of 3 screens, make it one long screen where you see the entire "window" view with a virtual overlay of other important info (like a simulator)

    - Would be great for a windowless cockpit
- Think outside the box
- Projection Displays
    - External light is a distraction…may not be an issue for a windowless cockpit
    - Fail-safe in a sense because the display doesn't go bad or you don't lose it
    - Good if vibrations are LOW
- Organic LED work…look into this
    - No off-axis viewing
    - Field of view issue (focal length)
    - Cognitive tunneling
- Video immersion – spherical display/virtual reality
    - So could see all views (up, down, side, etc)
- Mig21's and Mig29s – have ability to just look at the enemy and shoot, so don't have to have target in the HUD to shoot
    - Is there some applicability for this here?
- TRACS systems
- Synthetic Vision fused with the enhanced vision or radar data is the next step
- Electronic checklists
    - Needs improvement from current state
    - Currently tells you what to do, you dot it, then you must check it off or tell computer you did it with 2 checks or confirmations
        - People don't like this
    - Changes color as you complete a task
- EVS/SVS
    - Terrain has more texture the closer you get
    - When you do something extreme, the display completely changes (details, extra info go away) to get the pilot's attention
    - Have the whole window to see, but if weather takes away visibility, then you can look down at the synthetic vision and fly that way

6) NASA Johnson Space Center Meeting

Date: June 29, 2005
Duration: 5 hours
Conducted by: Cristin Smith

Summary:
Habitability and Human Factor Office at JSC

- Mihriban Whitmore
- Cynthia Hudy
- Vicky Byrne

Discussed NASA requirements for displays and general human factors issues

- Must consider internal lighting
- Must be redundant with another method of coding (i.e. Text & Color or "tooltip")
- Design without color and determine strategic places to color
- Going from 3D physical components (such as an AID) → 2D components
    - You might loose some information
    - Interesting study
- Automatic procedures viewers (automated checklists)
    - Japan uses them extensively
    - Manual procedures viewer
    - Intentional procedures viewer
- Astronauts drive the requirements
    - Usually a "crew advocate" on design team
- Gave me DGCS (Design Guidelines for Cockpit Station)
    - Design requirements agreed upon by all nations for the ISS
    - Not necessarily NASA requirements/guidelines

GN&C Autonomous Flight Systems Branch at JSC

- Jeremy Hart
- Ryan Proud
- Mark Jackson (Draper RICE)

First got a tour and demonstration of the Shuttle CAU (Cockpit Avionics Upgrade) Simulator, then we discussed function allocation and a tool that they had developed.

- Shuttle CAU
    - Abort options illustrated pictorially
    - Colors used to indicate which abort landing locations (CONUS and Overseas) were reachable depending on level of failure (# of engines out)
    - Very complicated/tedious procedures to tell shuttle which abort landing site you want to reach.
    - Nothing tells the crew if they have indicated they want to land at a site that is no longer a reachable option (basically figure that the ground will be double-checking everything)
    - To Abort

        - 1) Indicate which display unit your are controlling by pressing "DU (display unit) #"
        - 2) Choose option such as abort, RTL, etc by pressing "item # enter"
        - 3) Turn knob to RTLS
        - 4) Tell computer which abort site to go to by pressing "item # + #(LS number) enter"
    - "Soft Button" = bezel buttons
        - Can change with/on LCD
    - Every Display could change to any other display
    - Same options at bottom of every display screen (consistent across screens)
- FLOAAT (Function-Specific Level of Autonomy and Automation Tool) (Hardy, 2005)
    - Automation = human vs. computer
    - Autonomy = on-board vs. on-ground
    - Tool used to do function allocation
    - Process
        - Observe, orient, decide, act (OODA types)
        - FLOAAT questionnaire
        - FLOAAT automation/autonomy scales
        - Design implications
    - Determining the balance of authority
        - Delineation of decision –making authority must have clear/good requirements in the area of the exploration systems
    - Standard method to determine the appropriate balance of this authority
    - Quantitative assessment tool that…
        - Was developed for use during the requirements development process to quantitatively determine the appropriate levels of autonomy and automation to be included in the requirements
        - Provides NASA with a baseline reference for designing the appropriate level of autonomy and automation

References

Hardy, J., J. Hart, R. Proud. (2005). *Function-specific Level of Autonomy and Automation Tool*.

7) Mr. Steve Paschall II, Draper Laboratory
Date: June 29, 2005
Duration: 1 hour
Conducted by: Jessica Marquez

Mr. Paschall's expertise lies in landing simulations. He is part of the guidance, navigation, and control team at Draper for the Lunar Access project. This was the first of two meetings.

Summary highlights:

- Discussed the roles of guidance, navigation and control
    - Comparing where you are vs. how to get there vs. executing a plan
- Discussed the suite of sensors considered for the lander
    - Combination of radar, lidar and cameras.
- Landing phase priorities
    - Interested in terrain, what it looks like, correlating it to the map data base
    - Terrain relative position
    - Algorithms – feature matching

8) Mary Kaiser, PhD, NASA Ames Research Center

Date: July 5, 2005
Duration: 1 hour
Conducted by: Jessica Marquez

Dr. Mary Kaiser's expertise lies in human motion perception, visually-guided control, and dynamic spatial display design.

Summary highlights:

- Determining how much control does a lunar lander crew have on the spacecraft? Is it a first order or a second order control task?
    - Our displays designs should assist in executing the control task.
    - Control task is not trivial as the instincts that people have developed on Earth will not be appropriate on the Moon (new set of heuristics).
- Visual cues: limited to windows and should be coupled with the spacecraft state.
- Based on her time to contact research (within artificial displays) she is familiar with, people are looking at the ratio of objects to determine this contact time.
- Key parameters:
    - Fuel, lateral movement, and descent movement.
- Representing rates, using scale with grid
    - Sink velocity or rate: this would equate to an expansion of the grid
    - Forward velocity or rate: this would equate to the rate in which the grid lines pass "under" you.
- Review of initial display:
    - Suggested additions: show "future" trajectory, show effects of inputs, impact on trajectory and fuel.
    - Perspective of "outside" view needs improvement: what is the point of view? Alignment?
    - Ensure cognitive translation and integration between LZ and profile displays (facilitate mapping between them). Add projection of path to LZ display.
    - Positive feedback for including 2D (profile) and 3D (LZ) perspectives.
    - Need to consider: redesignation example. How do we represent redesignations that are either to the left, right, in front, and before an obstacle? This is difficult to integrate into one display.
- The added value of having a human in the loop for landing on the Moon is that they will be able to react to automation failures and mechanical malfunctions.

9) Miwa Hayashi, PhD, and Robert McCann, PhD, NASA Ames Research Center
Date: July 7, 2005
Duration: 2 hours
Conducted by: Jessica Marquez

Dr. Miwa Hayashi and Dr. Robert McCann both work at the Intelligent Spacecraft Interface Systems Lab. Their expertise lies in human factoring and spacecraft simulators. Dr. Hayashi also gave me a demonstration of their Space Shuttle cockpit simulator.

Space Shuttle cockpit simulator:

- Demonstrated new display developed under CAU, which is the redesign of shuttle displays.
- Simulator contained these interesting elements:
    - Fault management screen; instructed how to correct for fault. Could select for "accept automation" solution. Furthermore, it highlights the display of importance (information) for the fault/warning.
    - Display dials (and similar) were grouped together by task and "relatedness"
    - Horizontal situation display: shows trajectory
        - Had altitude vs. velocity

Summary highlights:

- Vertical navigation display is good for situation awareness
- Timeline important for mode awareness
- System status: should be used for health of critical components.
    - Could also use to see the consequences (or effects) of changes
- Crew role allocation
    - Commander: doing "most" of the work
    - LMP (pilot): should be the one to come up with the contingency plans
- Other possible ideas:
    - Integration of enhanced vision and profile view
    - "Pathways in the sky" (concentric squares and converging on landing site)
    - Displays on helicopters
    - HUDS displays like in cars, overlaid symbology
    - Abort, emergency situations that lay outside the norm; for example, resorting to deviating fuel from ascent phase to save the crew.
- Fuel envelope, similar to CAU display

10) Captain John Young, Apollo 16 Commander and Space Shuttle Astronaut

Date: July 6, 2005
Duration: 20 minutes
Conducted by: Cristin Smith

Download wav file: http://web.mit.edu/aeroastro/www/labs/halab/lunar.html

Transcript:

1) When were you first able to see the landing site? I understand that the first time you were able to see it was after pitchover, but were you able to see it well enough at that point to determine obstacles and redesignate if you needed to?
    a. Yep, and we did. We redesignated a little bit, not much. You could see everything you could…they had made a really good landing model in the simulator of the flight and you could recognize the craters that we had to land at and we could see all of them. It was really good…we also delayed for 3 orbits, so the sun angle we had was a little higher and when you got close to the ground you could see the shadow of the LM coming down just like a helicopter. So, you really didn't need a radar altimeter, you could just look at the shadow coming down and tell how fast you were coming down and look and see where you were going. We were lucky I think having a higher sun angle for landing, you won't need a radar altimeter if can look out the window and see the sun, see the angle but some places it won't round like the south pole, Lincoln basin, on the rim of shackleton crater I don't think the sun angle will be right for seeing the shadow.
2) Inside the vehicle was it smooth, was there any "turbulence" or shaking?
    a. Real smooth. You could feel the descent system oscillating a little bit, but it wasn't too bad. I recommend you read the Apollo Summary reports written back in 1975 I think.
3) As to the window that you used for viewing and redesignating your landing site, did the shape and sizes of it limit the options you had of places to redesignate your landing site to? I know fuel was the limiting factor, but were there places that you could have reached, but couldn't redesignate to because you couldn't see them out your window?
    a. No, I think the window was about the right size. What you want is a small window but you won't be able to see everything. And if the window was close to the pilot you could have seen a lot better. The problem was the window was out a little ways and you couldn't get really to it because you were strapped in. But you could see everything you need to see to fly. It was a pretty good window. Actually it was a lot bigger when we started and they discovered that besides being way outside the weight you could carry and most of the things you were looking at were parts of your spacecraft and you know you don't want to be looking at your spacecraft. So we sliced it down a lot. We had to or we wouldn't have the weight to land on the moon. I think you need to put the window right in front of the pilots eyes and you can see everything you need to for all the redesignation

stuff and you can probably have a HUD that will allow him to go anywhere he wants to with the gas he has remaining…or she or whoever is flying it.

4) I noticed through my research that you actually had to accept the radar data by pressing a button. Was the purpose of that a result of a lack of trust in the radar or what was the purpose of you actually having to accept it?
    a. No, the ground you know if the radar wasn't reading right the ground would know that and tell you and you wouldn't press the button. And if it was really off, you would have known if you looked out the window.
5) This wasn't really an issue for Apollo, but one of the things we've been talking about is the issue of a sensor mismatch. I realize that you had just the one landing radar but in the future we may have several sensors telling us the same piece of information. Even for you there were multiple ways to determine a piece of information…looking at the graphs and comparing, etc. Was there ever a mismatch between those and if so, what was the protocol this?
    a. Well I'm sure we had many of mismatches in the simulators and I don't remember what we did, but I'm sure that after we did it so many times we knew exactly what altitude we were at over what crater and that was just the kind of stuff you knew by heart because you knew it was so important. Because you'd done it so much in the simulators that you just know if the altimeter tells you one thing, you just look out the window and saw where you really were depending on where you were before when the radar said something. You know, you know. It was kind of a learning thing. Of course you can do that if you have good models of the surface and I'm sure we'll have good models of the surface next time we go. I heard that lunar orbiter was going to get good stuff. We had a rate of descent altitude controller and if you just you were coming down at a rate of descent and you hit that thing one time and if you wanted to stop it you'd hit it up and if you wanted to go down faster you'd hit it down. And every time you'd hit it you'd add a foot a second or subtract a foot a second to your rate of sink. So you could pretty well control your rate of sink. If you had to fly over a crater, you'd just stop it up completely and fly right over it and add some sink rate to get on down
6) So you position yourself directly above the landing site and then increase your rate of descent?
    a. Yep. You stop everything and increase your sink rate to a couple, three feet a second to get on down before you ran out of gas.
7) When you were coming in, you were coming forward. If there was an obstacle would you ever have the option to redesignate behind you?
    a. I guess you could, but no one ever did I think I don't' think
8) But it's because of where the window was…
    a. Yeah you'd have to be redesignating to a place you couldn't see and that wouldn't be too good.
9) Could you yaw the vehicle to see behind you?
    a. Yeah, you could yaw around. A yaw around would probably run you right out of gas. We had about 30-50 seconds of gas remaining when we hit, but Apollo 11 was just about out of gas when they touched down.

10) With respect to the use of “nouns” and “verbs” for communicating commands – I realize this was an artifact of the guidance computer, but was this an efficient/good method for communicating information
    a. You didn’t use that while you were flying. You couldn’t do anything with while you were coming down at the last moment. We had our S band antenna wasn’t right so we had to manually input 18 5-digit characters in the DSKY to input the state vector and get the thing started. That was pretty tedious and I was worried about getting that right
11) That was at what point in the landing?
    a. That was when we were just starting up the LM, during checkout, before deorbit. You were using nouns and verbs for late entries of stuff later but you don’t have very many strokes that I remember of course I don’t even remember what we did with them.
12) Did you feel like you had enough time between when you pitched over and could see the landing sites – I believe that was about 2 minutes you had. Did that feel like enough time?
    a. We practiced this whole business many, many time…thousands of time. I probably had about 40 or 50 landing in the lunar training vehicle. So, you know, we practiced and the lunar training vehicle ran out of gas fast too…it didn’t have much gas either. So, it trained you to get down
13) Do you feel that if you had had more time to evaluate the landing site, it would have been beneficial?
    a. We touched down about as flat as you could touch down, in about a 75 m crater. Couldn’t have done any better. Unfortunately the place we landed at was just nothing but the ancient hilly on the front side of the moon. In fact we only knew the surface to 20 meters…so we really didn’t know a lot about the surface. The basic data we had was 20 m resolution.
14) Prior to actually landing, was there an actual designated landing site or was it a landing area?
    a. We had a landing site. I forget what it was. There were three craters and we were supposed to land next to them. We didn’t have to, that’s just where they said we ought to land in terms of the extravehicular activities that were planned. We only missed it by 75 yards I think. Wasn’t too bad
15) From talking to other astronauts, one issue they have brought up is the issue of scale. When you landed on the Moon it’s not like there was a house or person there that you could use to judge.
    a. Telling distances was really difficult. It had no relationship to anything you’ve ever seen before. We landed so late we could see the shadow coming down. The footpad of the LM was 32 feet across and you could see the footpads coming down and you could tell the size of the craters. I could see down in the shadows and bottoms of the craters.
16) You talked a lot about having the high sun angle and how beneficial that was and I realize it was a fluke from the orbit delay.
    a. Yeah, well I think that maybe an orbit delay aught to be nominal. Maybe you aught to do that all the time. As a backup to your radar altimeter if you land with the sun at your back. It wasn’t nominal because they would have

had all these arguments. You had to have the sun angle at this amount. It was 7.8 degrees and it had to be that and it couldn't be another angle. I forget the reason why.

17) The digital autopilot…what exactly did that include?
    a. Well, you were flying digitally and your flying attitude control and its flying throttle control and flying your altitude rate of descent meter. I don't' know what all else it included …not much cause we only had 36,000 words. We had the primary plus strap on system.
18) You had to actually turn it on though, right?
    a. You turned it on and aligned it with the stars using the telescope and you had to put in the right reference matrix so you knew where you were when you started so it'd navigate to where you were going and stuff like that.
19) Turning it on was just part of the startup of the LM?
    a. Yeah, LM checkout. You wouldn't want to undock till you had it all aligned and set.
20) Could you please explain the abort procedures?
    a. We just pushed the abort button and you'd be on your way
21) There was just one button?
    a. Yeah, as far as I know…one guidance system. You just push it and on your way… We had it fixed for our mission. It was really user unfriendly with 10,000 strokes or something to operate and if you fail one stroke you're done for. So, we had that fixed for our mission. I think that A14 guys before us had it fixed and they were ok with that. If you made a mistake your abort guidance system would crash. You couldn't afford for that to happen. There were a lot of computer programs like that if you fail one input you fail the whole thing, which considering there might be a thousand key strokes to do it…that's just crazy.
22) There has been talk of a windowless cockpit or synthetic vision
    a. Yeah, I know they're talking about synthetic vision. But I still think you aught to have real visual system up there because the human beings still want to stay alive and you give them a window and they can see out the window. When the synthetic vision system goes out, falls apart or something, they're dead. That's crazy.
23) What if there was still a window for backup purposes, but primarily depend on the synthetic vision?
    a. I think you could do that. I tried to get them to put in synthetic vision system for the space shuttle. You know they agreed to landing in 0/0 weather as apposed to bail out in the shuttle and they won't use synthetic vision for that either cause if takes a lot of software and they don't have it.
24) What is 0/0?
    a. Zero visibility, zero ceiling. You know because that sometimes occurs up the east coast when you're going to Canada and past Canada.
25) After PDI when there were some residuals between your predicted and actual paths and then Houston would upload the new RLS
    a. Yeah, noun 69, they would do the state vector upgrade as you came over the horizon they would do that uplink.

26) Was that redesignating to the new predicted site or back to the original site?
    a. It could only do downrange…nothing laterally. Yeah, it would tell the descent engines you were either short or long. That was discovered and fixed for A12.
27) What did landing feel like? Did you feel like you were moving fast towards the surface?
    a. No, you had sink rate set up and as soon as the probes hit the surface, you'd shut the engines down and it was a drop.
28) In all the Apollo missions, I know that all of the commanders took over manual control. Was this a lack of trust in the automation? What was your reasoning for taking over manual control?
    a. Because the place we were landing was saturated in craters and the automatic system didn't know where the heck the dang craters were and I could look out the window and see them. Why trust the automation anyways? You're responsible for the landing. You know where you want to land when you look out the window and why don't you make sure you land there? It's not a big deal.
29) The LPD designator…was each little hash mark equivalent to one "click" of the hand-controller?
    a. I sure don't remember. I can't remember that far back. I might try some of the lunar module handbooks.
30) Were you only able to redesignate during LPD mode to places you couldn't see on that scale?
    a. No, you could redesignate anywhere you wanted to or take over manually and fly where you wanted to. It wasn't a big thing.
31) What do feel is the role of humans in the next mission to the Moon?
    a. I think they ought to go to the Moon, get out and explore it. And you know if the South Pole Lincoln basin really does have water, that'll really be something. If it has all the big craters and lot of them have the metals, we can do that. I think when we industrialize the moon in the next century we'll be able to get reliable ____ from the United States. You know, the risk to human beings because of civilization being destroyed because of either an asteroid or super volcano is 1 in 455 in the next 100 years – that's very high risk. By industrializing the moon, we can save the people on earth and that's what we should be doing. That's pretty high risk. People don't realize how high risk they are because they've never heard of super volcanoes, but of course Yellowstone is a super volcano and long valley caldera's a super volcano and every one of them is alleged to go off any second. If Yellowstone goes off it'll wipe out the breadbasket of the United States and the rest of us too.

11) Dr. Gary Spiers, NASA Jet Propulsion Laboratory

Date: July 11, 2005
Duration: 2 hours
Conducted by: Jessica Marquez

Dr. Gary Spiers is the team lead in the Lunar Access project for the Lidar. Among present in our meeting was Andrew Johnson and two other Lidar team members.

Summary highlights:

- Lidar, in general was discussed.
    - Outputs: maps and altitude, hazard identification (depends on a "cost", which can be slope, roughness, altitude)
    - Capabilities: range and beam area (foot print)
    - Limitations: compounding of factors (albedo, angle of incidence, and roughness) to determine hazard; correcting for uncertainty (velocity of spacecraft)
    - Benefits: how it improves upon future Moon map resolutions
- At the time, there was no plan yet for the Lidar to point at the landing site. Considering only point in the lidar direction during the descent (braking) phase.
- Had a brief discussion about comparing previous mapping data with new Lidar information. Autonomous landsite selection ought to be what the astronaut would select (i.e., comparable algorithm for searching)

12) AV-8B Harrier and MV-22 Osprey Simulators

Date: August 1, 2005
Duration: 10 hours
Conducted by: Cristin Smith

The AV-8B Harrier and MV-22 Osprey simulators were arranged for by Capt William Grant and conducted by 1Lt Arthur Bruggemen (BruggArt80@aol.com) and Mark C Thoman (mthoman@comtechnologies.com) at Cherry Point Marine Air Station, NC (Harrier) and New River Marine Air Station, NC (Osprey).

Justification: The AV-8B Harrier and MV-22 Osprey are the closest aircraft on earth to a lunar lander in terms of "flying" to their target site much like a conventional aircraft, but landing vertically like a helicopter. The tools they use to conduct this sort of flight as well as the cognitive process involved are extremely applicable to a lunar lander.

AV-8B Harrier

The AV-8B Harrier is a V/STOL (vertical/short takeoff and landing) military aircraft primarily used by the Marine Corps. The Harrier is used to conduct close air support, deep air support including reconnaissance and air interdiction, antiair warfare, and deploy to and operate from carriers, expeditionary airfields, and remote tactical landing sites ("AV-8B Harrier", 2005). The Harrier is capable of vertical landings and takeoffs using moving nozzles that direct the thrust of the engines. The picture below illustrates an AV-8B performing a vertical takeoff or landing.

Figure 1 AV-8B Harrier

MV-22 Osprey

The MV-22 Osprey is the world's first production tilt-rotor aircraft. It is used by the US Marine Corps, US Navy, and US Special Operations Command to conduct combat missions. The tilt-rotor aircraft combines the speed, range and fuel efficiency normally associated with turboprop aircraft with the vertical take-off/landing and hover capabilities of helicopters (NavAir, 2005). The pictures below illustrate the MV-22 flying like a helicopter, capable of vertical take-offs and landings, as well as it flying like a normal turboprop aircraft.

Figure 2 MV-22 Osprey

Summary:

<u>AV-8B Harrier</u>

- What are the 3 most important pieces of info that you use during a vertical descent?
    - Attitude
    - Altitude
    - It's actually very visual. "I usually move the aircraft (yaw) until I see two landmarks like those two buildings out there in the distance, and I use them to sense my sink rate and any lateral/translational velocity"
    - This is key information – Harrier pilots are primarily not on the instruments during a vertical landing
        - No landmarks of known size on the Moon – must provide crew with this information
- Key info included on the HUD = airspeed, altitude, barometric setting, aircraft G, angle of attack, heading, ground speed
- Rate climb/descent is in fps – negative = descent
- Must check to see if vehicle is able to hover prior to hovering
    - Based on outside temperature and vehicle weight
- HUD for VSTOL Mode (see below)

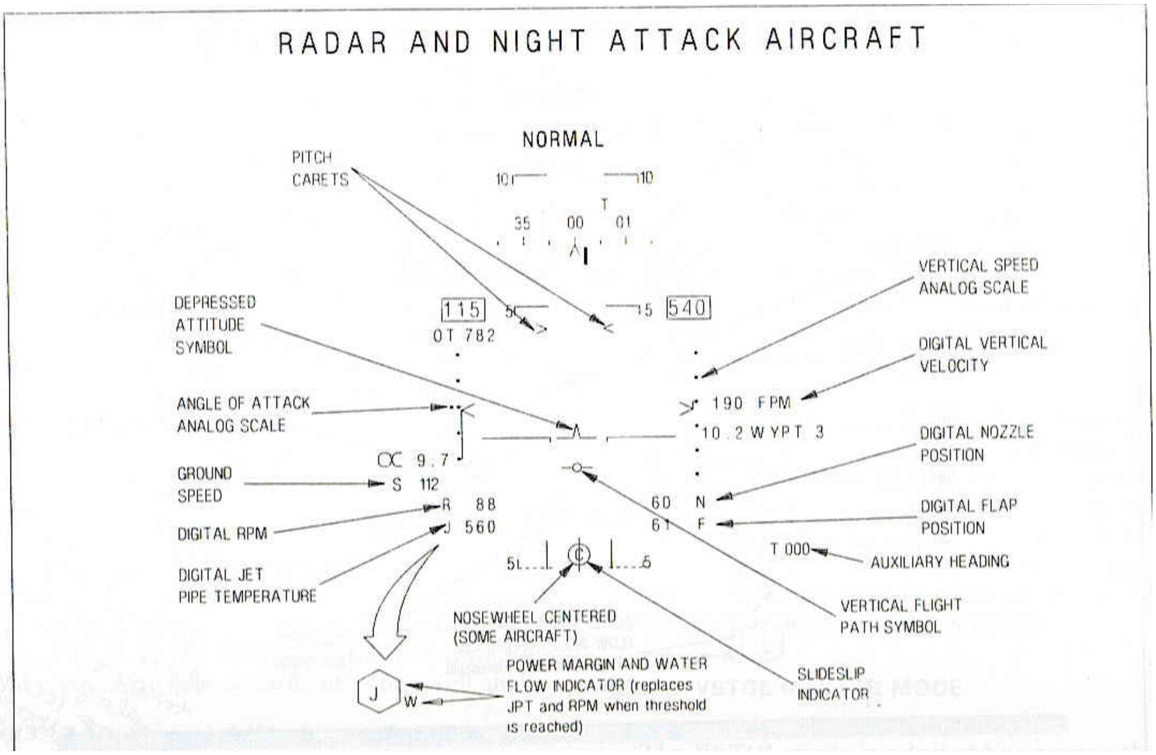


Figure 3 VSTOL Mode HUD Symbology (*AV-8B Harrier NATOPS Manual*, 2000)

- When VSTOL mode is selected, a vertical speed analog scale appears in the HUD (*AV-8B Harrier NATOPS Manual*, 2000)
    - Provides trend information during climbs and dives
    - Scale range = +1500 to -2000 fpm with graduations at +1000, +500, 0, -500, -1000, and -1500 fpm.
    - Moving caret has reference line connecting it to the zero graduation when it is displaced from zero
    - Jet Pipe Temperature (JPT) is major thing to watch for the Harrier
        - When JPT is ~ 60 deg below maximum JPT or when rpm is ~ 6% below max rpm, the display becomes a growing hexagon around the letter J or R with each completed side representing a certain degrees or percentage of rpm (see above) → indicates mode change, attracts attention of pilot
    - Proper hover attitude
        - When horizon bar of flight path/pitch ladder is aligned with the depressed attitude symbol
    - VTOL display
        - Shows max weight of fuel and water (F+W) aboard the aircraft at which the vertical takeoff or vertical landing can be performed.
        - Pilot can manually enter some of the data needed to determine max F+W

MV-22 Osprey

- Agreed that vertical landings were primarily visual and that "out-the-window" views of landmarks, etc provided primary sink rate information
- VSTOL heads-down display

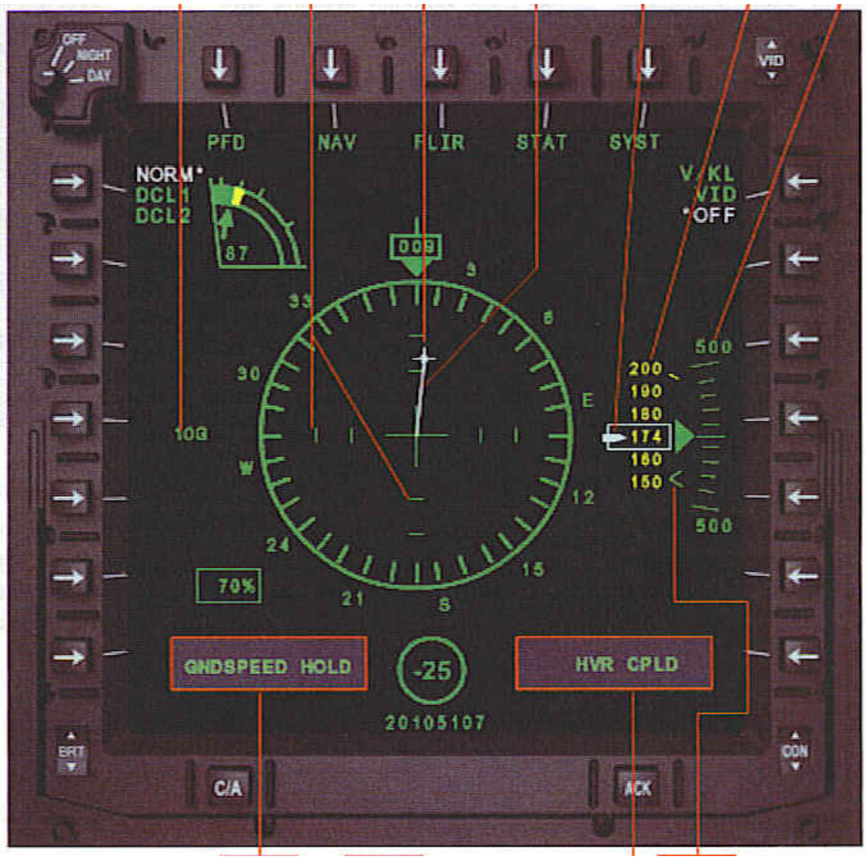


Figure 4 Osprey VSTOL Symbology (*MV-22 Student Guide*, 2005)

- Key information includes, groundspeed, velocity vector scale, acceleration cue, velocity vector, commanded radar altitude pointer, radar altitude, vertical speed range, caution/advisory/annunciator fields (*MV-22 Student Guide*, 2005)
    - Acceleration cue – provides a/c acceleration in the horizontal plane. The cue and the velocity vector are both interactive and dynamic. To hover over a spot, keep the acceleration cue over the center of the cross hairs.
    - Radar altitude scale is normally green, but turns yellow along with the box and digital readout when the actual readout is less than the radar altitude low set point
        - Disappears if radar altitude data becomes invalid
    - Dots show future path 10, 20, 30 seconds in the future
- Can pull up a FLIR (forward-looking infrared) image as background behind the top-down view of the velocity vector, etc.
    - Engineers/designers resisted the top-down view superimposed on the "out-the-window" view for a long time
    - Pilots LOVE it and find it very intuitive (according to instructor pilot, Mark Thomas)

- System status display
  - Top Level shows cartoon picture of vehicle with various subsystem layers accessible from the bezel buttons in the upper right corner

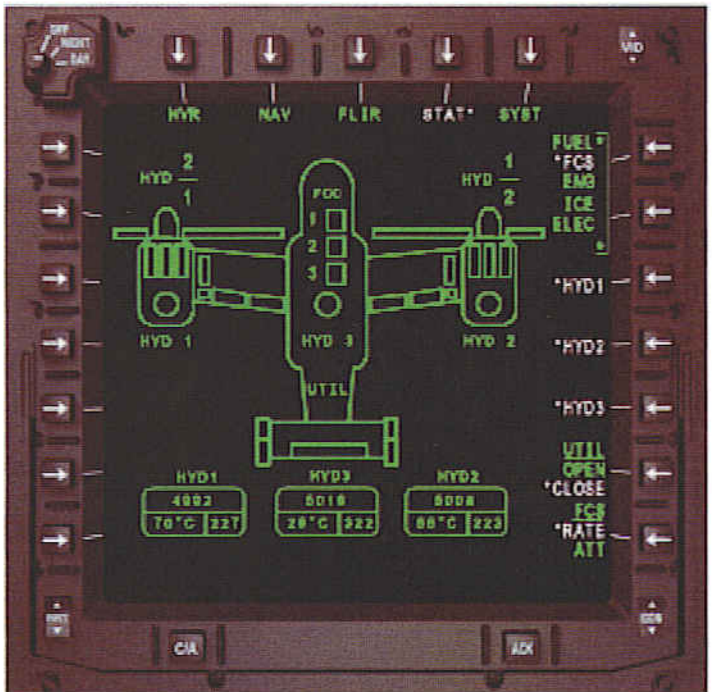
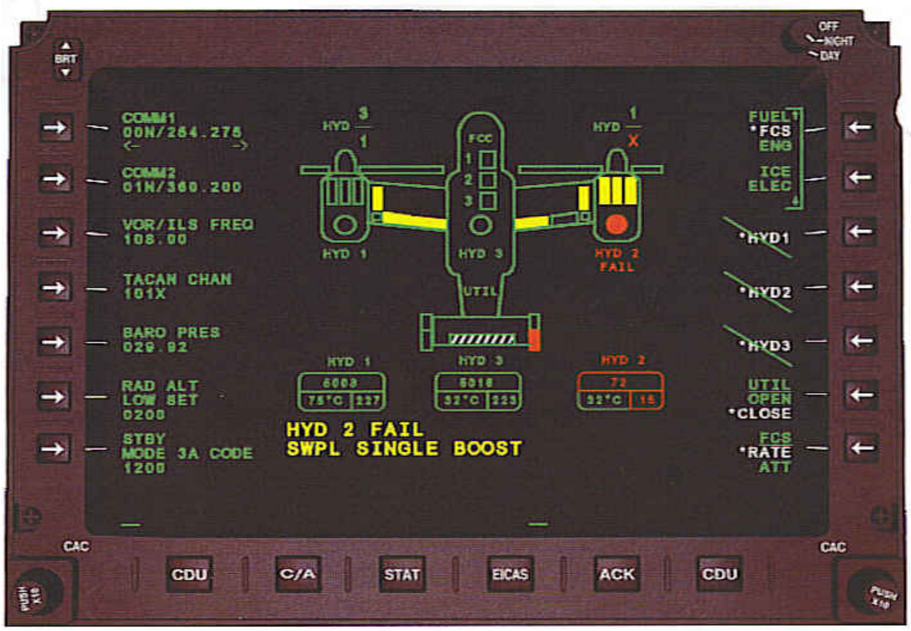


Figure 5 Osprey SS Nominal (*MV-22 Student Guide*, 2005)

  - In case of emergency or warning, the affected system lights up with a message



HYD 2 FAIL
SWPL SINGLE BOOST

Figure 6 Osprey SS Warning (Single Failure in Triple Redundant System) (*MV-22 Student Guide*, 2005)

    - Subsystem layers are also cartoon schematics of the system illustrating the redundancy of the system and the failure points.

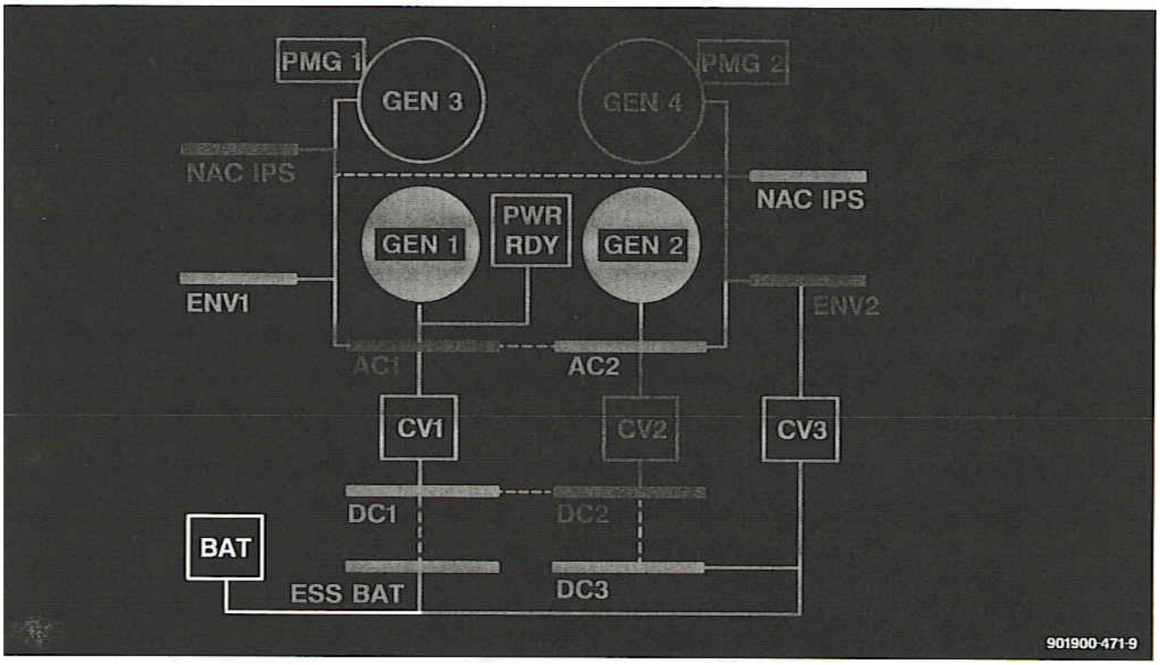


Figure 7 Osprey Electrical System Status Layer (*MV-22 Student Guide*, 2005)

- Aircraft is fly-by-wire and can be flown almost entirely using dials seen below.
    - Hover can be initiated this way be commanding a hover altitude at current or set altitude
    - Current parameter such as speed, heading, etc. can be put on "hold" to maintain current value

Figure 8 Control Dials (*MV-22 Student Guide*, 2005)

- Redesignation of landing site is a mental calculation of fuel, burn rate, and altitude to determine how far and for how long the pilot can hover/maneuver for landing

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MV-22 Student Guide. (2005).

NavAir (2005). *V-22 Osprey Web*. Retrieved 26 August 2005, from the World Wide Web: http://pma275.navair.navy.mil/

13) Buzz Aldrin, Apollo 11 Lunar Module Pilot

Date: August 15, 2005
Duration: 1 hour
Conducted by: Cristin Smith, Jessica Marquez, and Mark Duppen

Download wav file: http://web.mit.edu/aeroastro/www/labs/halab/lunar.html

A list of the questions that were asked during the interview with Buzz Aldrin is seen below. Some of the questions may not have been asked due to time constraints.

I. Role
   a. As the LMP, could you please explain your role during the landing phase in terms of what information you were monitoring, what information you were communicating to the commander, and the sequence of steps? Please use these pictures to help me understand what was going on in LM during the descent.

II. In my research of the Apollo landings, I have noticed that there were several methods for determining your current altitude, position, and speed and checking the trustworthiness of your radar.
   a. One of these methods was landmark tracking. Could you please explain how this was done and what information you were able to determine by doing this? Was Apollo 11 the only mission that performed landmark tracking? Why did the others not?
   b. Another tool was a chart that showed delta-h as a function of the time into the burn. This was compared with computer readout of radar data. Is this correct? Could you please explain how you did the comparisons and how you determined what tolerance was acceptable for a comparison of the two?

III. Landing Site Redesignation/Projection
   a. I understand that the scribe marks on the left window in front of the commander were used to determine to what landing site the guidance and navigation system was directing the vehicle. Could you please explain how the scribe marks on the window (the LPD) in conjunction with the readout from the computer on the DSKY were used to determine this landing site?
   b. Is it correct that there were two panes of glass with the scribe marks that must be lined up when looking through the window to accurately use the LPD?
   c. If the commander was not satisfied with the site where the LM was headed, how did he initiate a change?
   d. In this picture, there's some sort of table taped to the panel. Do you recall what this table indicated and how it was used?
   e. I found these illustrations of your landing footprint capability from the lunar landing symposium in 1964. Was this something you trained with, had on-board, or maybe never used at all?
   f. How did you know how far away you could redesignate a landing site?

   g. What do you think was the commanders reasoning when he was determining a new site?

IV. Decisions
   a. What do you recall as the major decisions that either you or the commander had to make during the descent of the LM?
   b. What information did you use to make that decision?
   c. How did you make that decision? What were the options?

V. Nouns/verbs
   a. I understand that you used “nouns” and “verbs” to command actions or receive data. Were the numbers associated with different actions and data something that you had to memorize as part of your training?
   b. Could you please look at this timeline of events and tell me if it illustrates the way that you recall the lunar landing taking place?

VI. Manual control
   a. In manual control mode, how was the vertical velocity or sink rate controlled? Could it be set to a constant value? Was sink rate automatic except when a hover was commanded?
   b. Did your role as the LMP change when the commander went into manual control mode? If so, could you please explain how it changed?

VII. Time
   a. I realize that there was a digital event timer onboard. What was this and how was it used?
   b. At any time, did you have a sense of or a way to check the time left until another event such as pitchover or landing took place? How accurate was this time?

VIII. Abort
   a. Could you please explain how an abort during landing would take place using these pictures of the panels? What were the steps that had to be taken?
   b. What were some of the criteria for aborting that you recall?
   c. I understand there were abort boundaries in terms of where you could abort to when using which engine. This figure is something that I found in document from the lunar landing symposium in 1964. Did you have something similar on-board to guide your abort procedures?

IX. Off – Nominal
   a. If an alarm sounded, did you have any way of determining what the problem was?
   b. Did you mostly depend on ground control during these off-nominal situations?
   c. What did you feel was your actual ability onboard to fix or work around an off-nominal situation?

14) Mr. Steve Paschall II, Draper Laboratory

Date: August 17, 2005
Duration: 1 hour
Conducted by: Jessica Marquez and Cristin Smith

In our second meeting, Mr. Paschall explained and discussed the current trajectory models and results that the GN & C team have been working on.

Summary highlights:

- Mr. Paschall had, previous to our meeting, emailed a few trajectory plots. He methodically explained the trajectory.
    - A trajectory can be viewed with many different parameters. He demonstrated how to correlate them appropriately.
- Three phases of the trajectory were discussed: braking phase, free fall, and terminal descent.
    - Phases were located in space and time.
    - We considered the reasons why the phases' duration would change. It was concluded that this mostly depended on the accuracy of the burns.
- Discussed was a comparison between Apollo trajectories and the new Draper trajectories.

Appendix B Display Screen Shots

Landing Zone Display

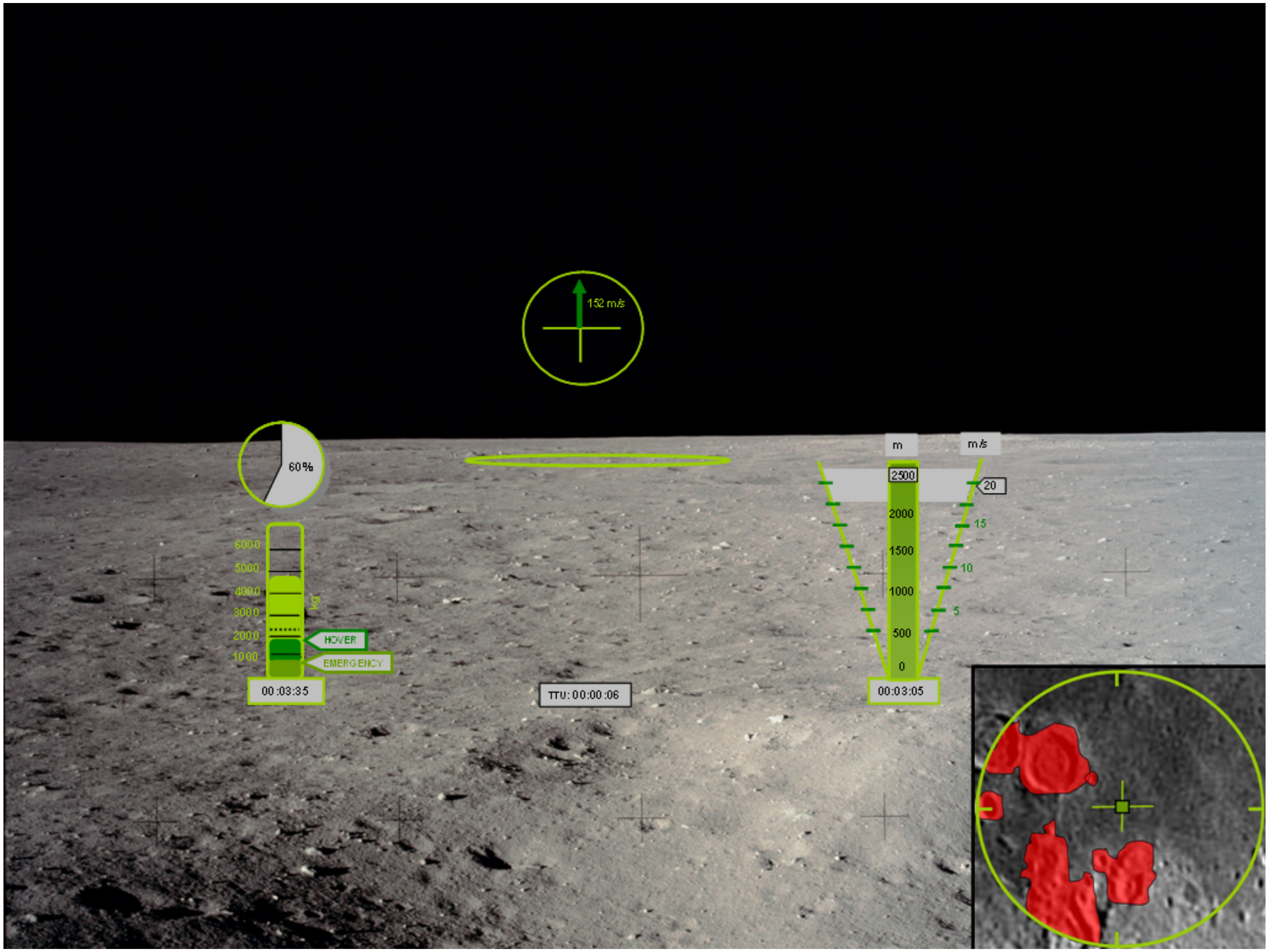


Figure 1 Screen Shot 1 (Pre-Terminal Descent Phase)

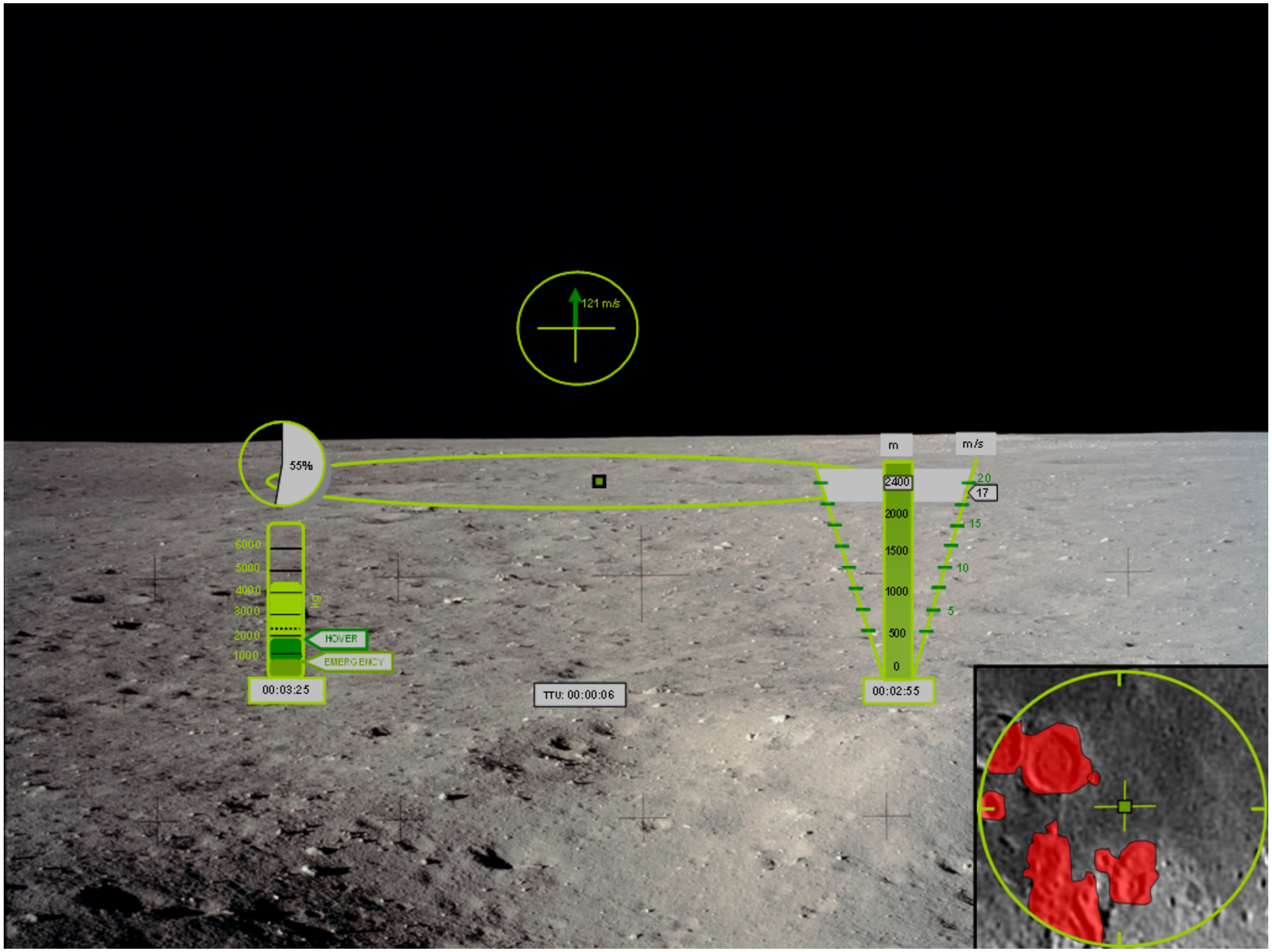


Figure 2 Screen Shot 2 (Pre-Terminal Descent Phase)

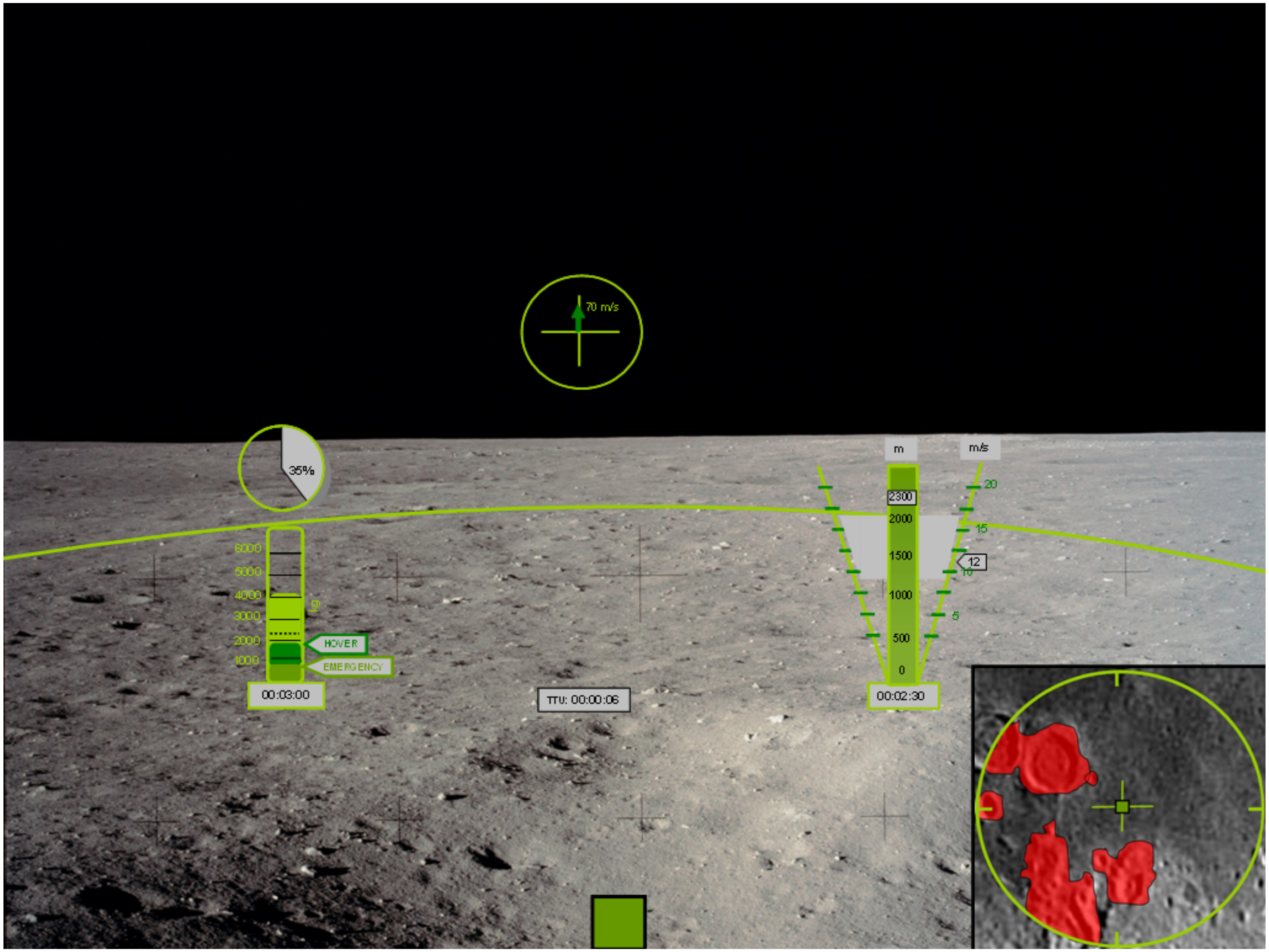


Figure 3 Screen Shot 4 (Pre-Terminal Descent Phase)

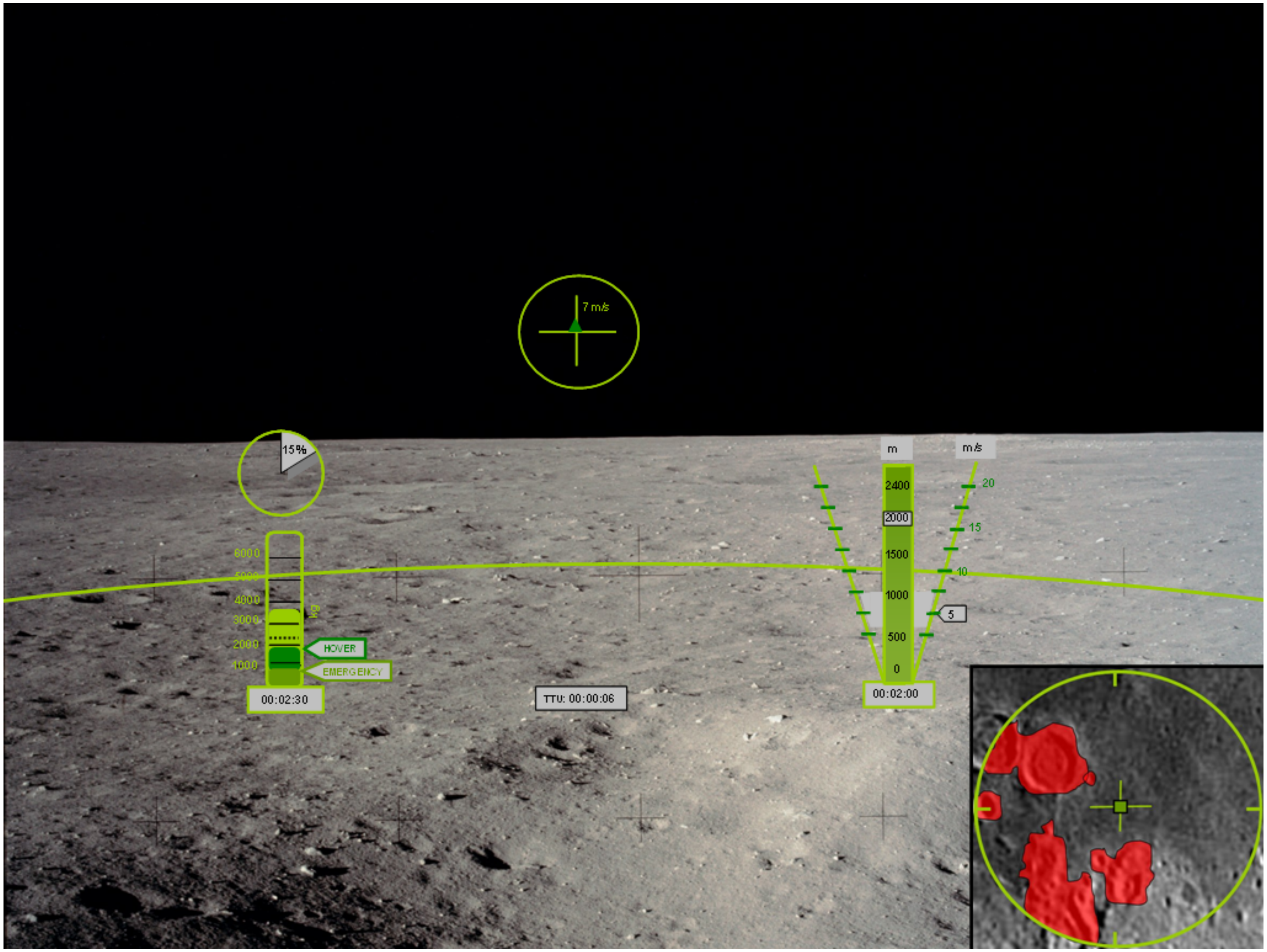


Figure 4 Screen Shot 5 (Pre-Terminal Descent Phase)

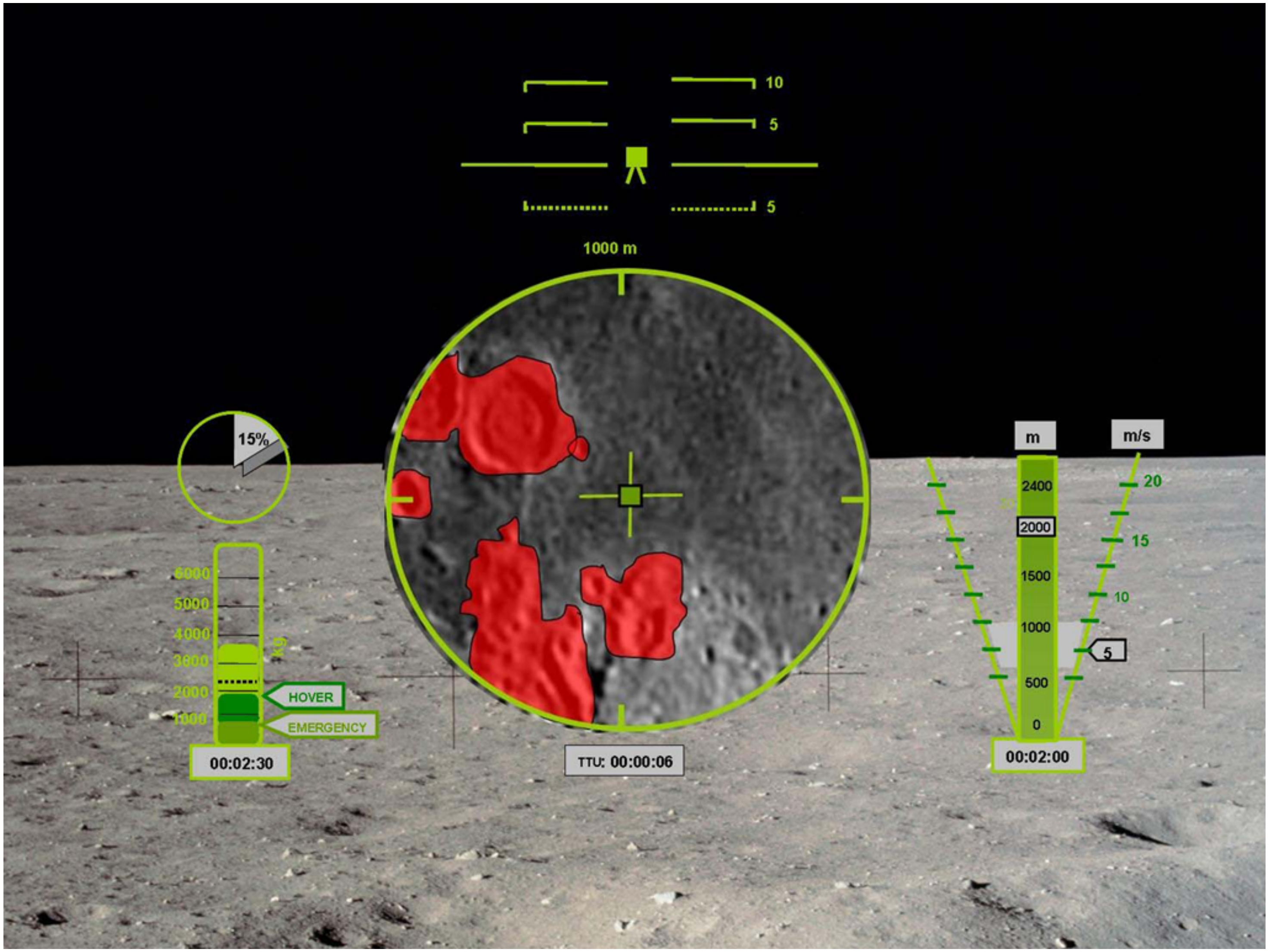


Figure 5 Screen Shot 6 (Terminal Descent Phase)

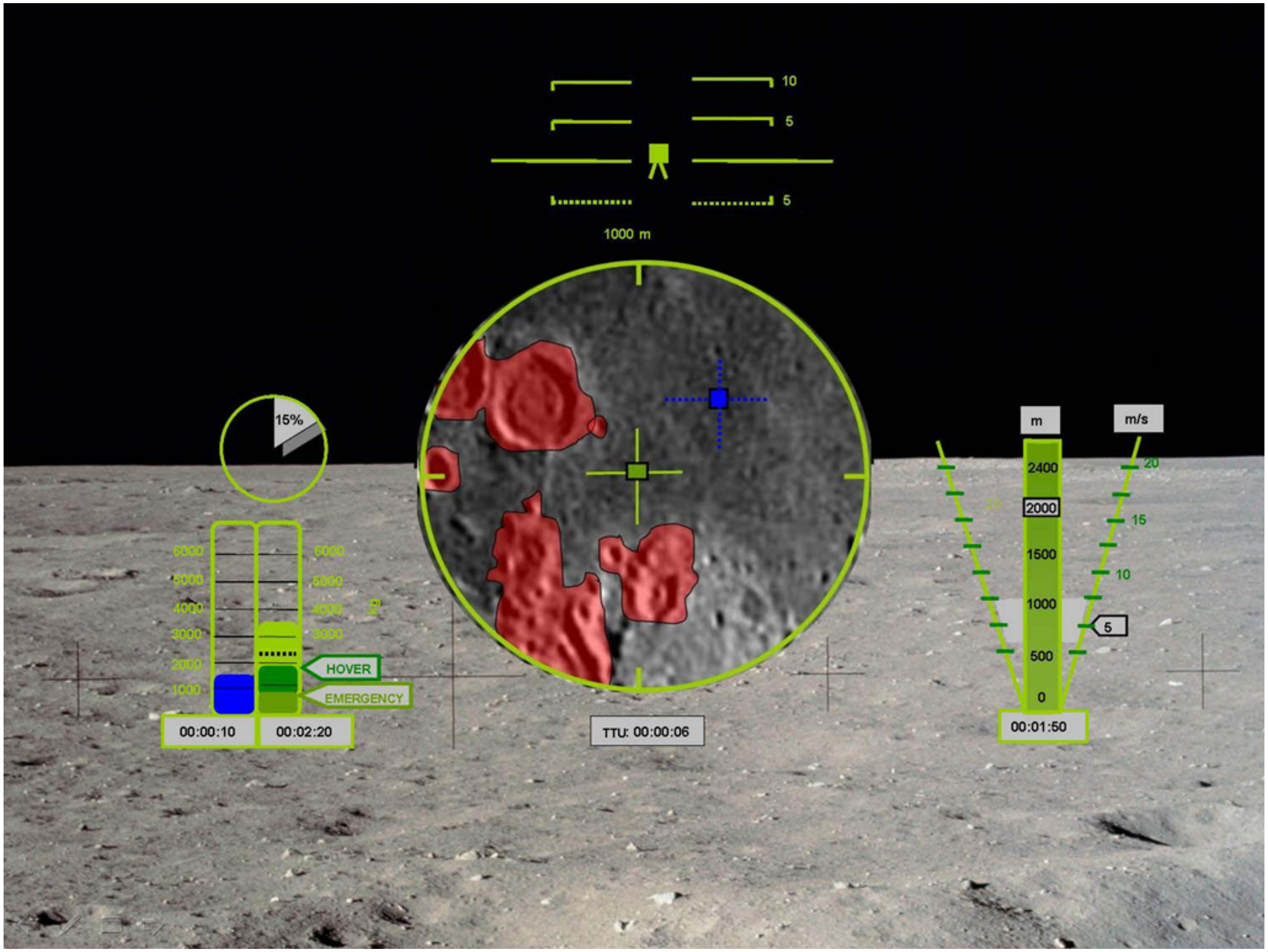


Figure 6 Screen Shot 7 (Landing Site Redesignation)

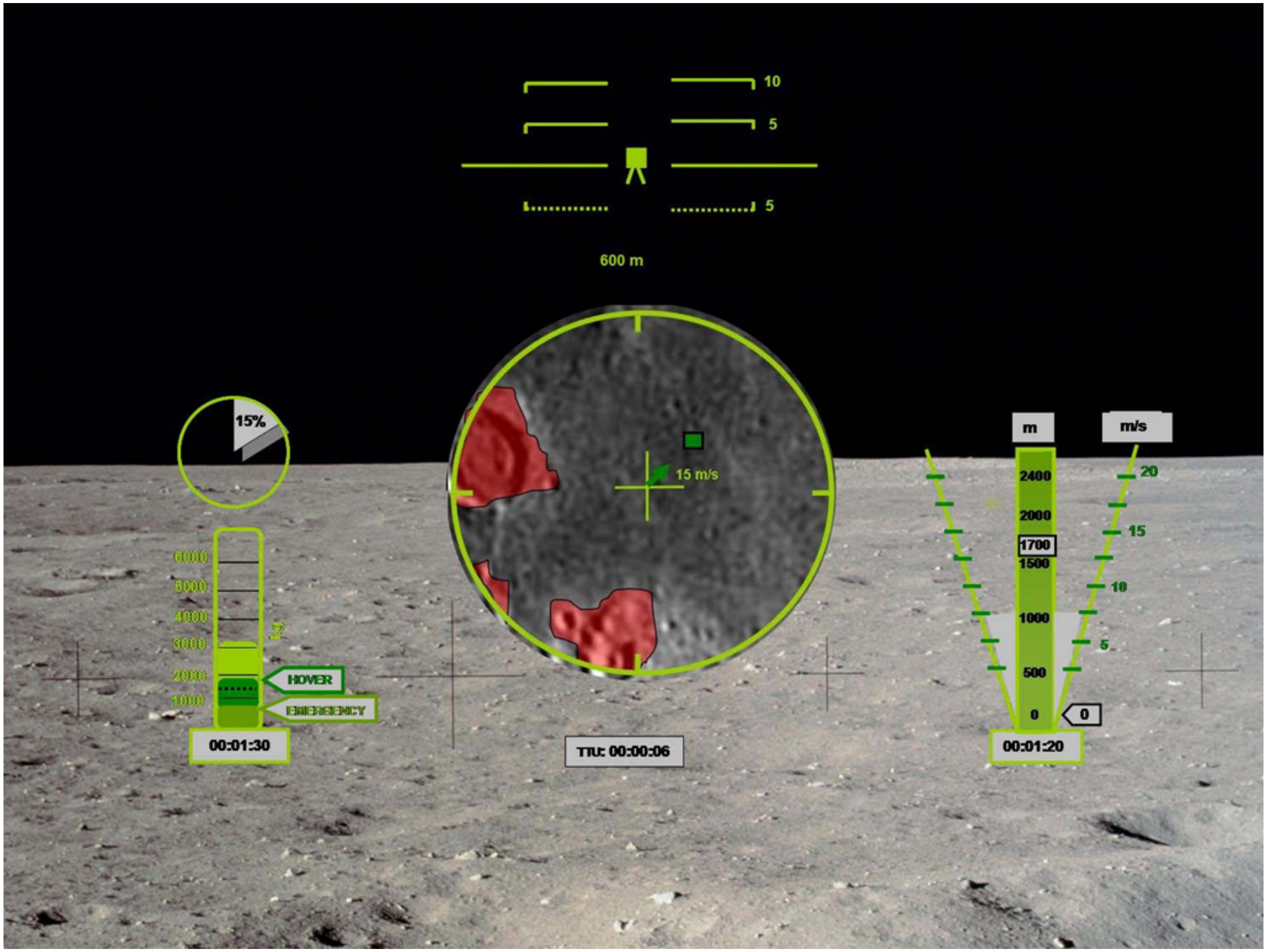


Figure7 Screen Shot 8 (Midcourse to New Landing Site)

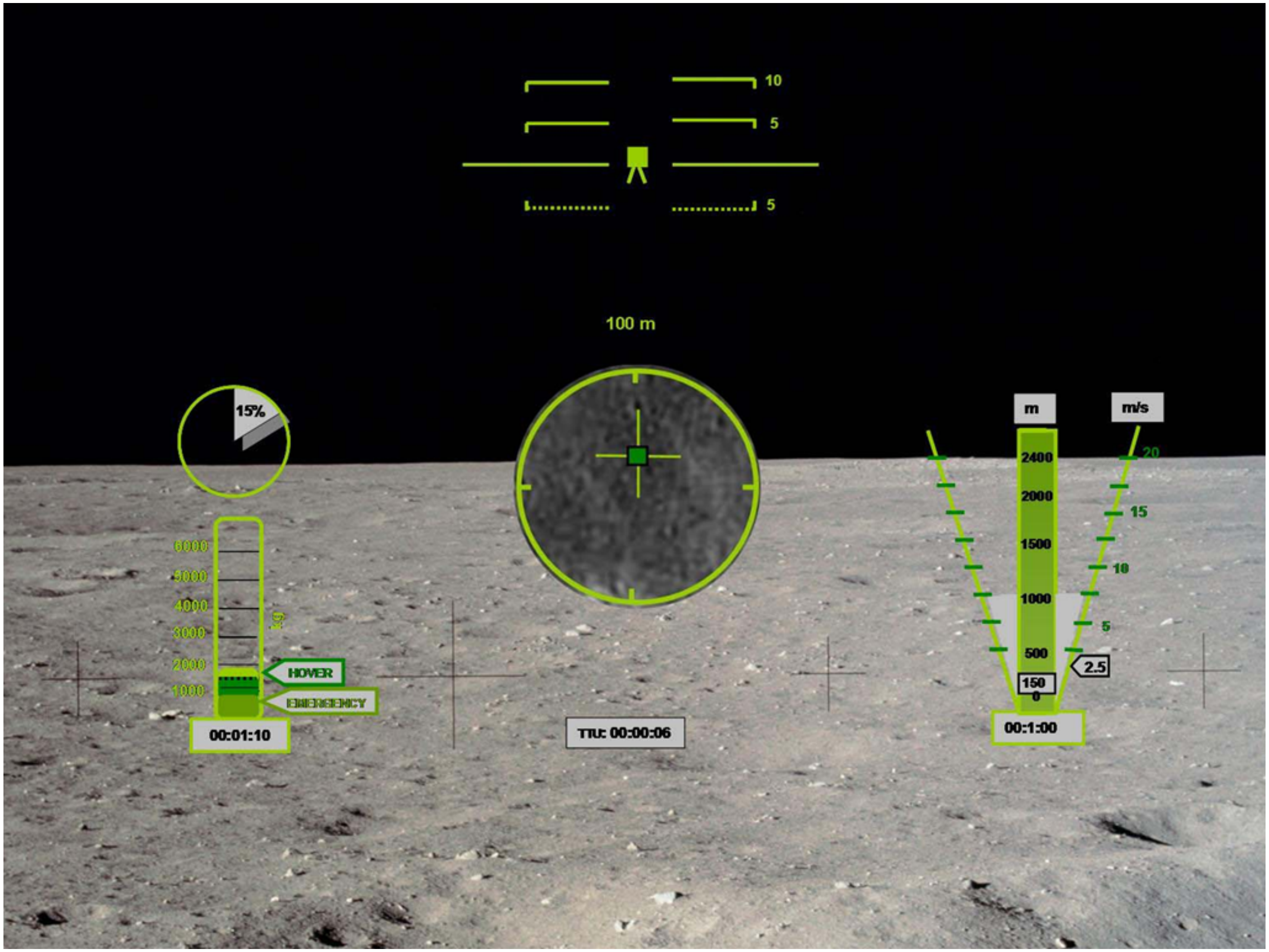
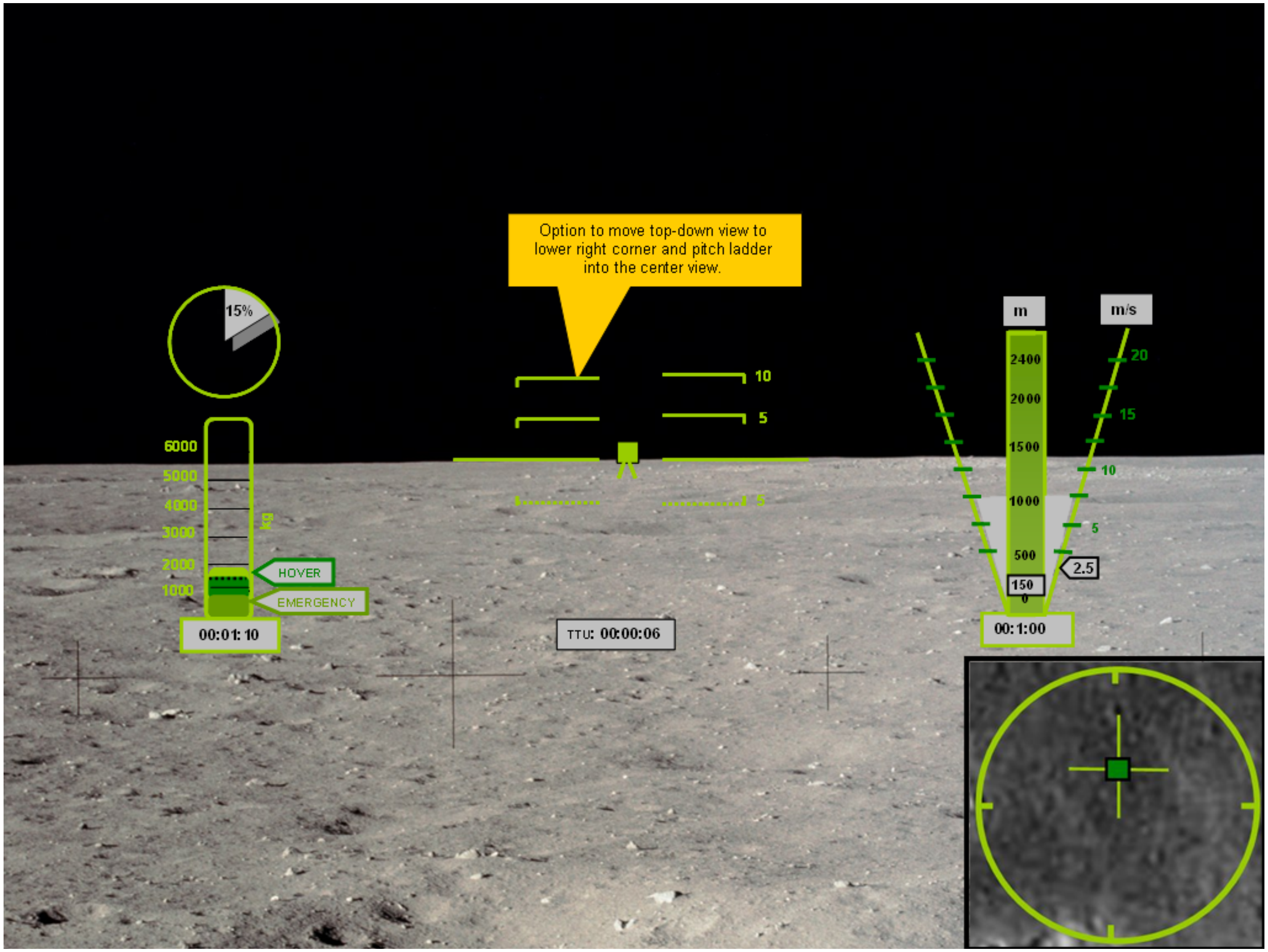


Figure 8 Screen Shot 9 (Arrival at New Landing Site)



Option to move top-down view to lower right corner and pitch ladder into the center view.

Figure 9 Alternate LZ Display Configuration

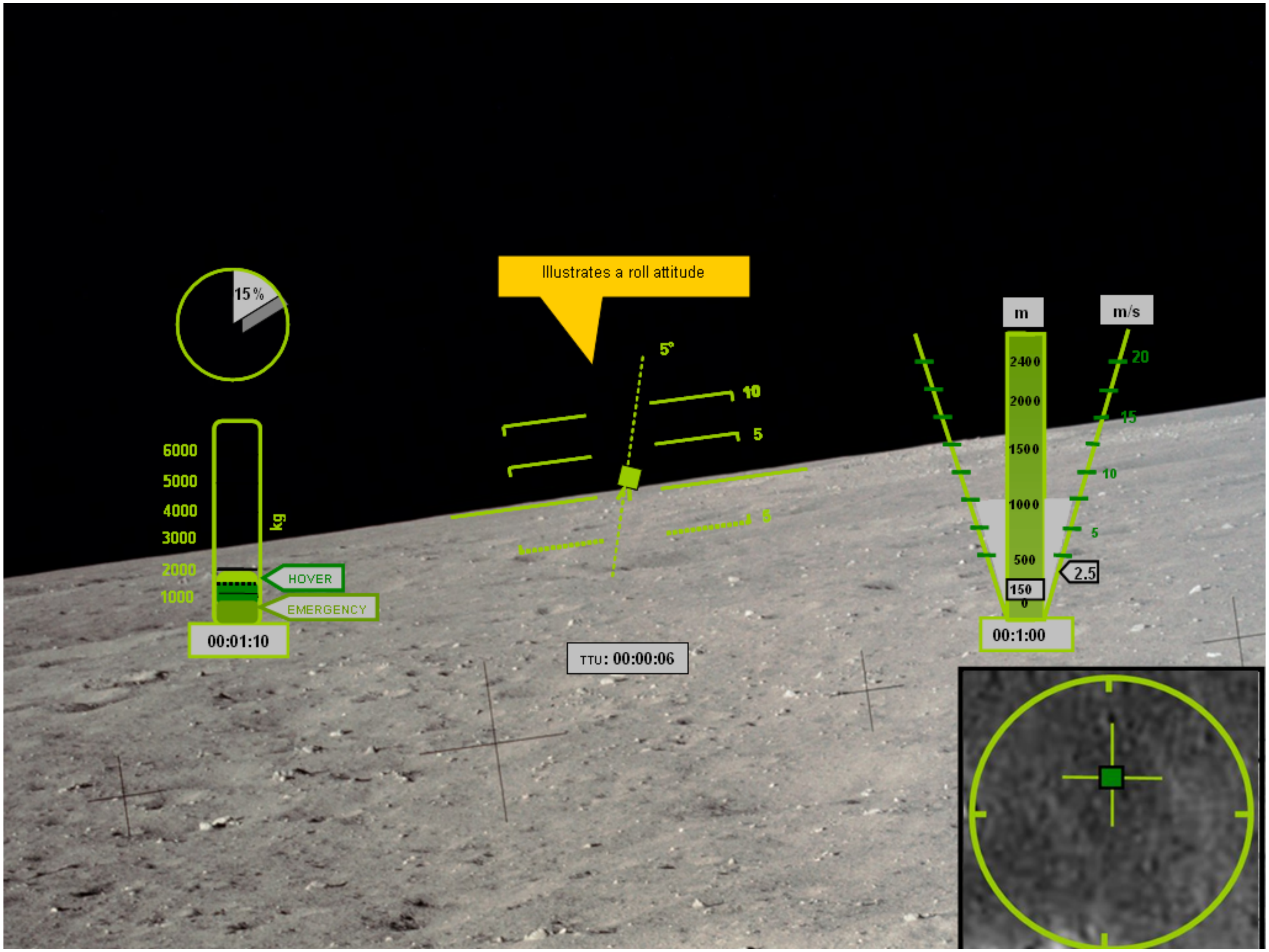
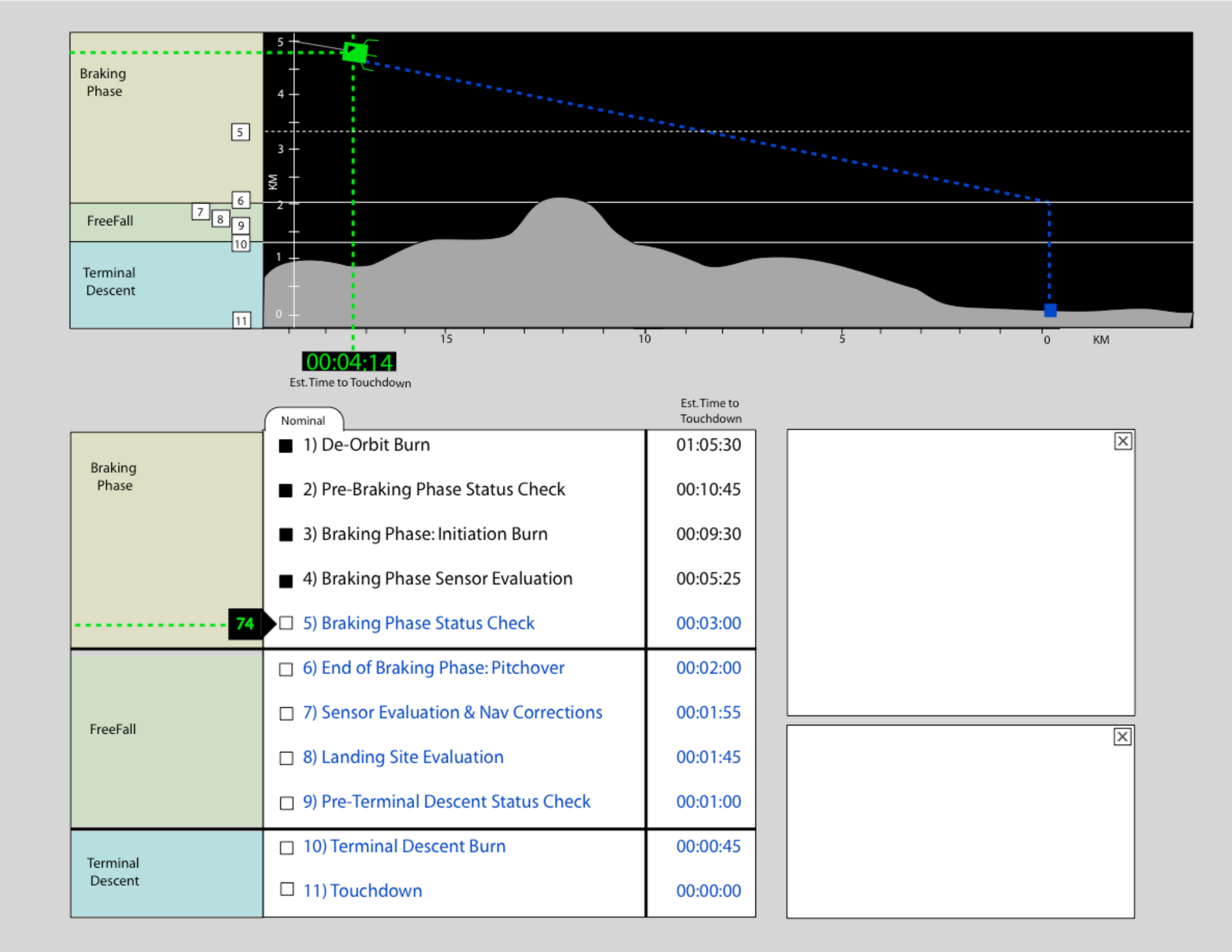


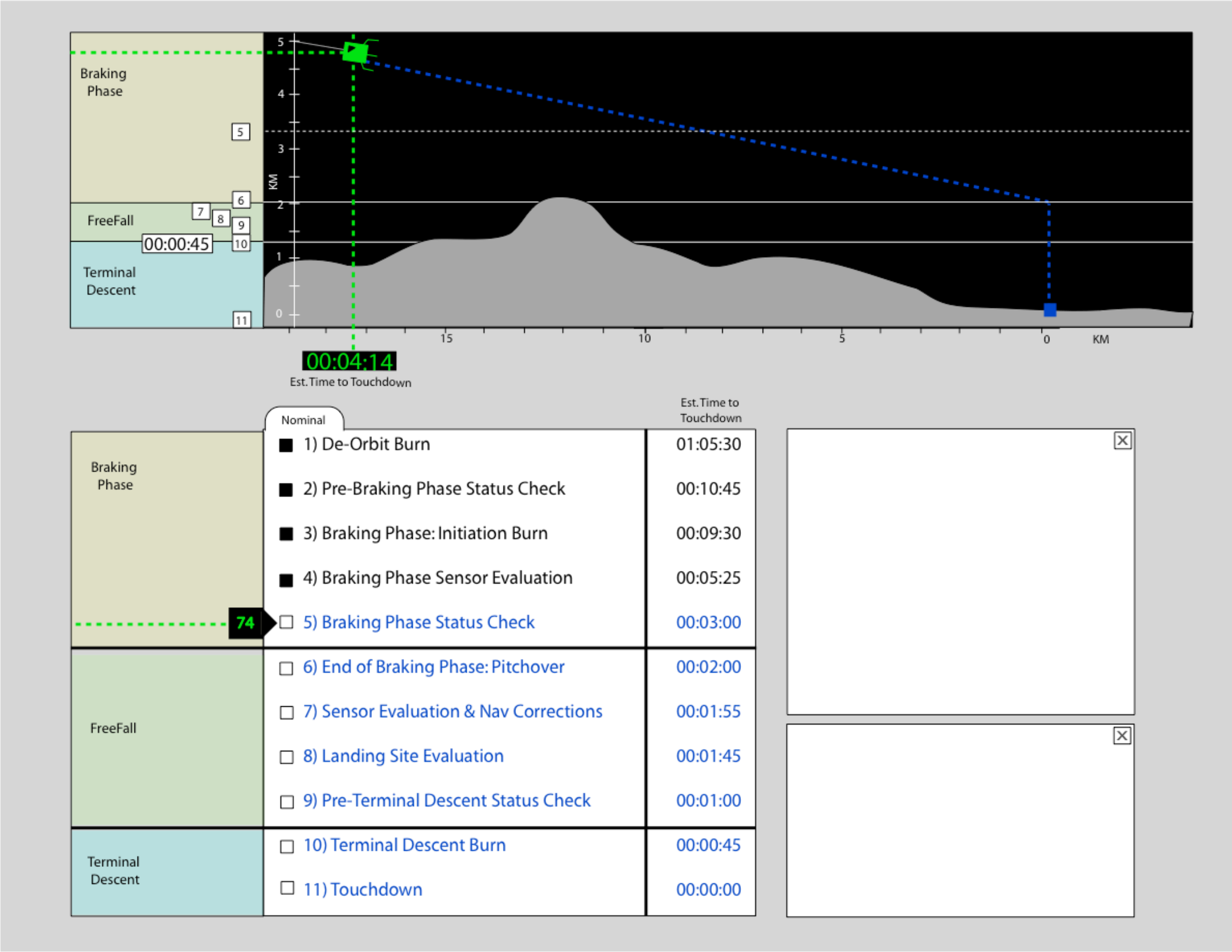
Figure 10 Roll Attitude Scenario

Situational Awareness Display



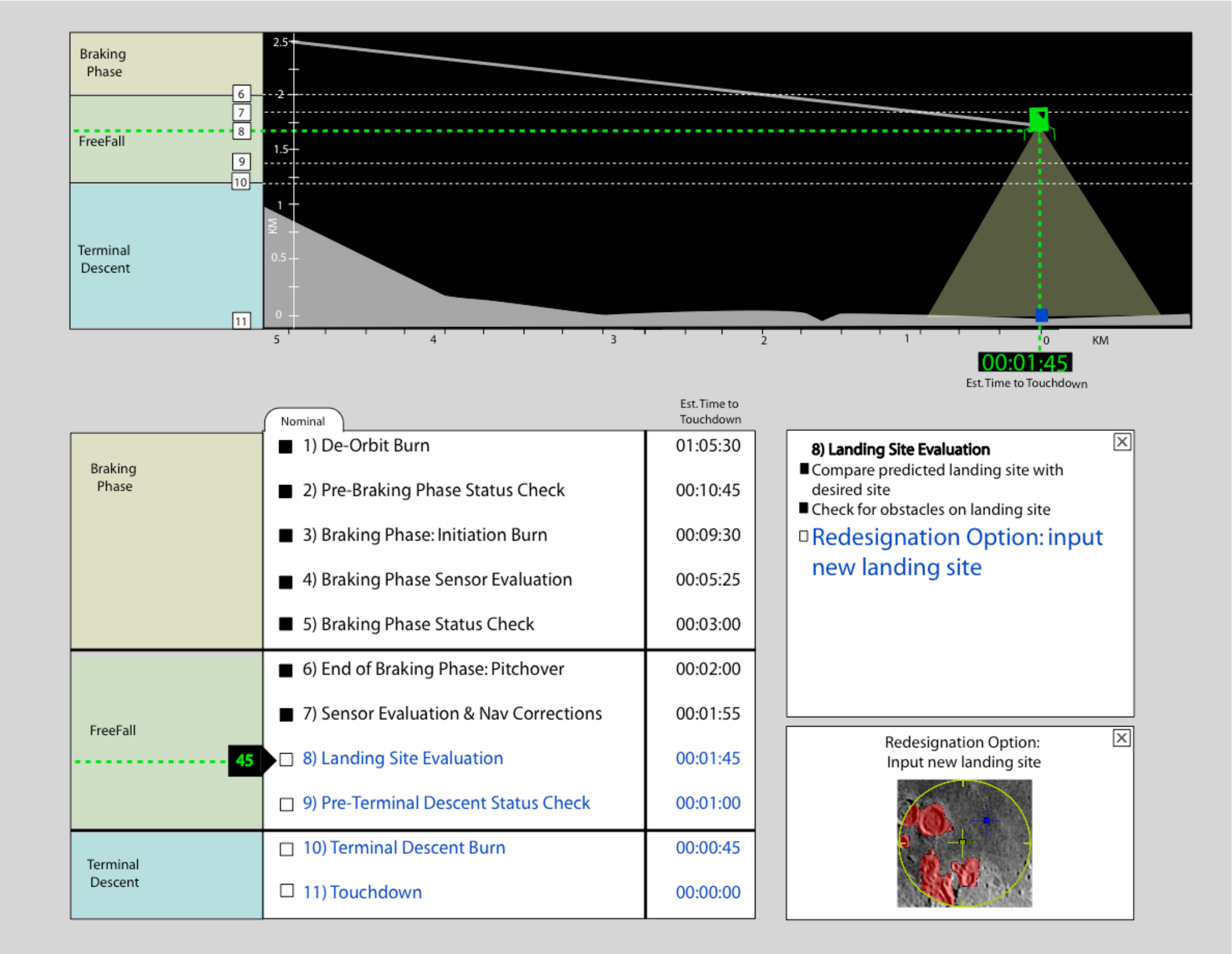
Phase	Nominal	Est. Time to Touchdown
Braking Phase	■ 1) De-Orbit Burn	01:05:30
	■ 2) Pre-Braking Phase Status Check	00:10:45
	■ 3) Braking Phase: Initiation Burn	00:09:30
	■ 4) Braking Phase Sensor Evaluation	00:05:25
	☐ 5) Braking Phase Status Check	00:03:00
FreeFall	☐ 6) End of Braking Phase: Pitchover	00:02:00
	☐ 7) Sensor Evaluation & Nav Corrections	00:01:55
	☐ 8) Landing Site Evaluation	00:01:45
	☐ 9) Pre-Terminal Descent Status Check	00:01:00
Terminal Descent	☐ 10) Terminal Descent Burn	00:00:45
	☐ 11) Touchdown	00:00:00

Figure 11 Basic Configuration of Situational Awareness Display



	Nominal	Est. Time to Touchdown
Braking Phase	■ 1) De-Orbit Burn	01:05:30
	■ 2) Pre-Braking Phase Status Check	00:10:45
	■ 3) Braking Phase: Initiation Burn	00:09:30
	■ 4) Braking Phase Sensor Evaluation	00:05:25
	☐ 5) Braking Phase Status Check	00:03:00
FreeFall	☐ 6) End of Braking Phase: Pitchover	00:02:00
	☐ 7) Sensor Evaluation & Nav Corrections	00:01:55
	☐ 8) Landing Site Evaluation	00:01:45
	☐ 9) Pre-Terminal Descent Status Check	00:01:00
Terminal Descent	☐ 10) Terminal Descent Burn	00:00:45
	☐ 11) Touchdown	00:00:00

Figure 12 Basic Configuration of Situational Awareness Display, with "Mouse-over" Time Highlighted



		Est. Time to Touchdown
Braking Phase	■ 1) De-Orbit Burn	01:05:30
	■ 2) Pre-Braking Phase Status Check	00:10:45
	■ 3) Braking Phase: Initiation Burn	00:09:30
	■ 4) Braking Phase Sensor Evaluation	00:05:25
	■ 5) Braking Phase Status Check	00:03:00
FreeFall	■ 6) End of Braking Phase: Pitchover	00:02:00
	■ 7) Sensor Evaluation & Nav Corrections	00:01:55
	☐ 8) Landing Site Evaluation	00:01:45
	☐ 9) Pre-Terminal Descent Status Check	00:01:00
Terminal Descent	☐ 10) Terminal Descent Burn	00:00:45
	☐ 11) Touchdown	00:00:00

8) Landing Site Evaluation

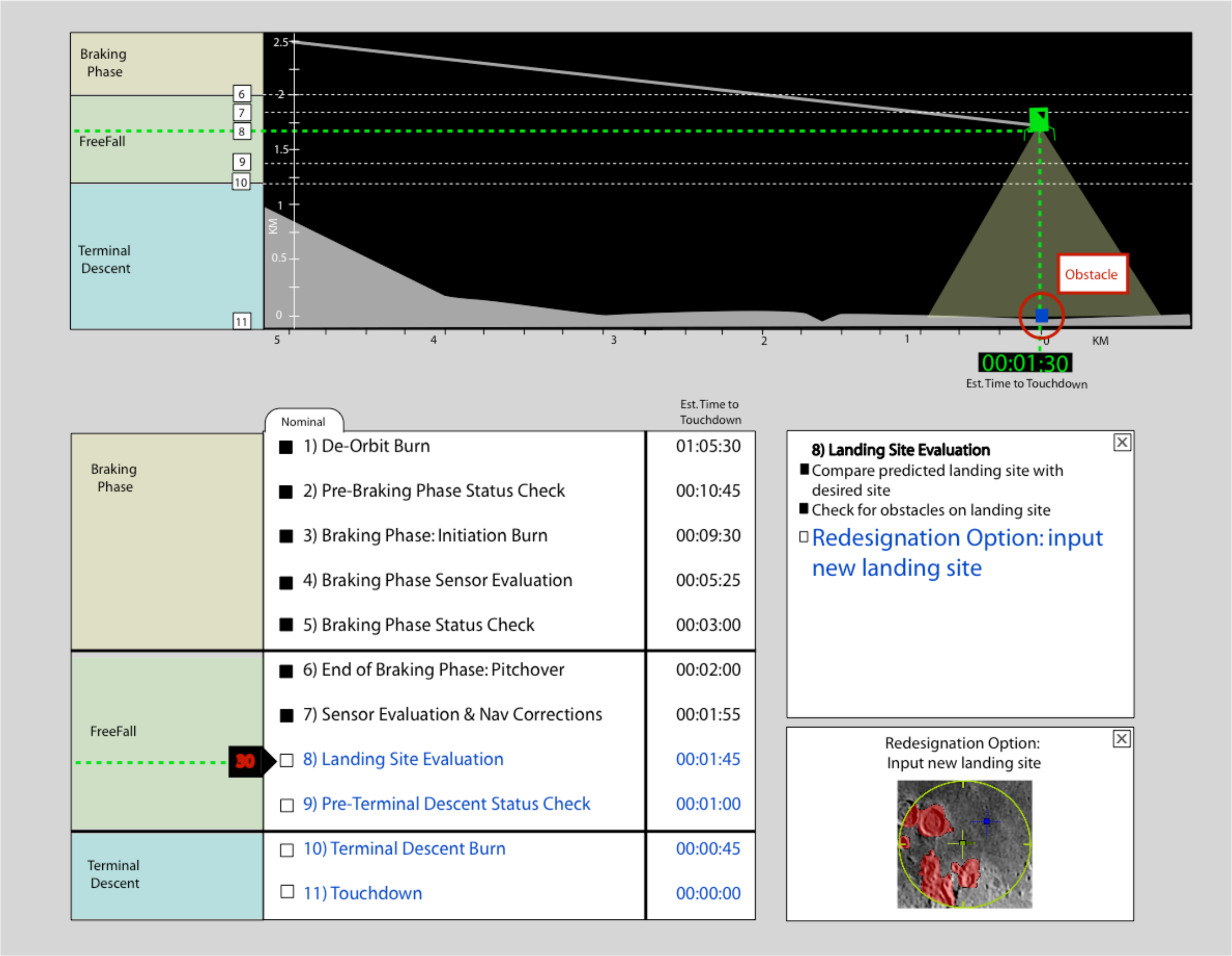
■ Compare predicted landing site with desired site

■ Check for obstacles on landing site

☐ Redesignation Option: input new landing site

Redesignation Option:
Input new landing site

Figure 13 Situational Awareness Display with Expansion Boxes Activated and LIDAR Display



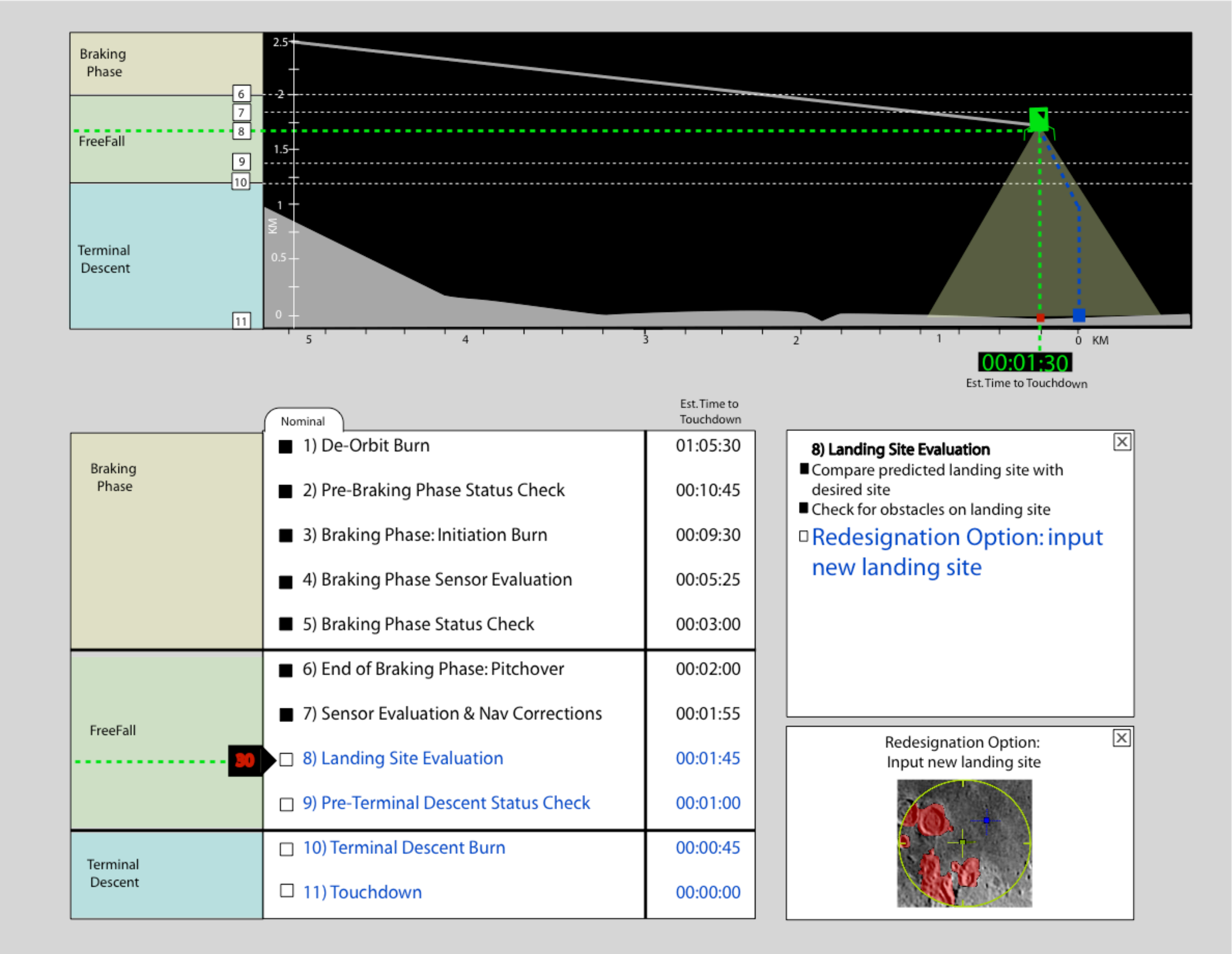
	Nominal	Est. Time to Touchdown
Braking Phase	■ 1) De-Orbit Burn	01:05:30
	■ 2) Pre-Braking Phase Status Check	00:10:45
	■ 3) Braking Phase: Initiation Burn	00:09:30
	■ 4) Braking Phase Sensor Evaluation	00:05:25
	■ 5) Braking Phase Status Check	00:03:00
FreeFall	■ 6) End of Braking Phase: Pitchover	00:02:00
	■ 7) Sensor Evaluation & Nav Corrections	00:01:55
	☐ 8) Landing Site Evaluation	00:01:45
	☐ 9) Pre-Terminal Descent Status Check	00:01:00
Terminal Descent	☐ 10) Terminal Descent Burn	00:00:45
	☐ 11) Touchdown	00:00:00

8) Landing Site Evaluation

- ■ Compare predicted landing site with desired site
- ■ Check for obstacles on landing site
- ☐ Redesignation Option: input new landing site

Redesignation Option:
Input new landing site

Figure 14 Situational Awareness Display, with LIDAR Detected Obstacle



Phase	Nominal	Est. Time to Touchdown
Braking Phase	■ 1) De-Orbit Burn	01:05:30
	■ 2) Pre-Braking Phase Status Check	00:10:45
	■ 3) Braking Phase: Initiation Burn	00:09:30
	■ 4) Braking Phase Sensor Evaluation	00:05:25
	■ 5) Braking Phase Status Check	00:03:00
FreeFall	■ 6) End of Braking Phase: Pitchover	00:02:00
	■ 7) Sensor Evaluation & Nav Corrections	00:01:55
	☐ 8) Landing Site Evaluation	00:01:45
	☐ 9) Pre-Terminal Descent Status Check	00:01:00
Terminal Descent	☐ 10) Terminal Descent Burn	00:00:45
	☐ 11) Touchdown	00:00:00

8) Landing Site Evaluation

- ■ Compare predicted landing site with desired site
- ■ Check for obstacles on landing site
- ☐ Redesignation Option: input new landing site

Redesignation Option:
Input new landing site

Figure 15 Situational Awareness Display, with Redesignation Trajectory

System Status Display

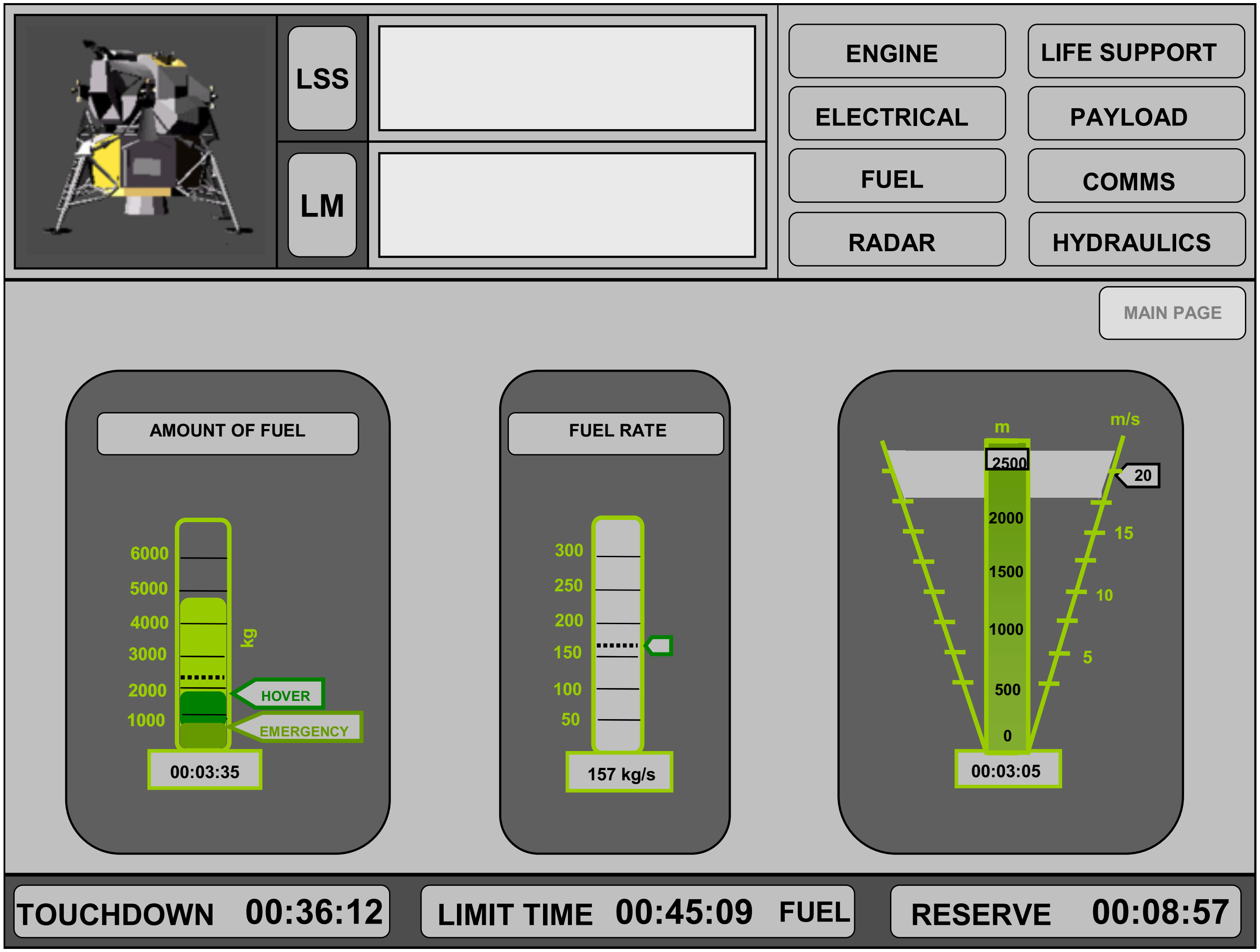
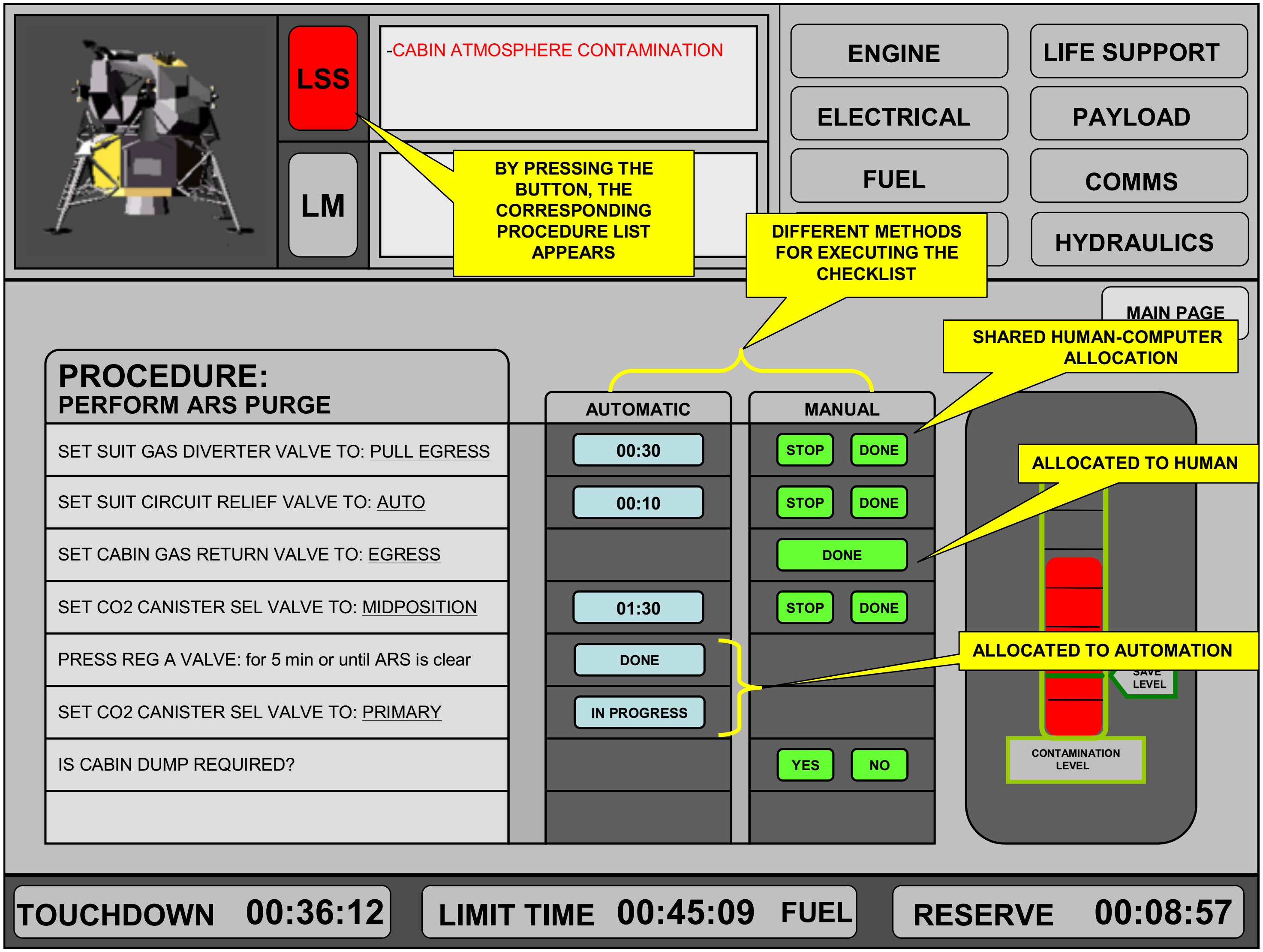


Figure 16 System Status Main Display



PROCEDURE:
PERFORM ARS PURGE

	AUTOMATIC	MANUAL
SET SUIT GAS DIVERTER VALVE TO: PULL EGRESS	00:30	STOP DONE
SET SUIT CIRCUIT RELIEF VALVE TO: AUTO	00:10	STOP DONE
SET CABIN GAS RETURN VALVE TO: EGRESS		DONE
SET CO2 CANISTER SEL VALVE TO: MIDPOSITION	01:30	STOP DONE
PRESS REG A VALVE: for 5 min or until ARS is clear	DONE	
SET CO2 CANISTER SEL VALVE TO: PRIMARY	IN PROGRESS	
IS CABIN DUMP REQUIRED?		YES NO

BY PRESSING THE BUTTON, THE CORRESPONDING PROCEDURE LIST APPEARS

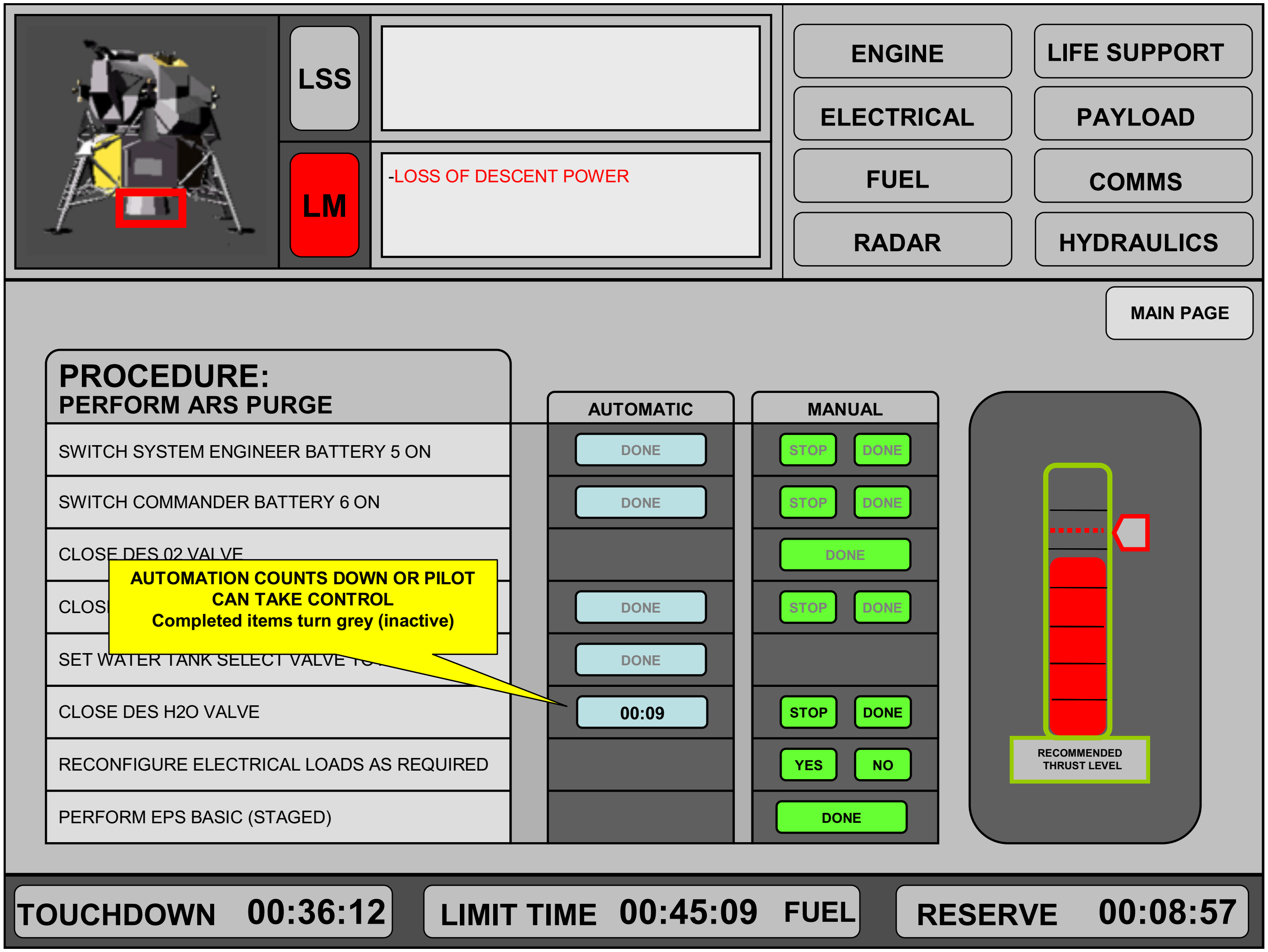
DIFFERENT METHODS FOR EXECUTING THE CHECKLIST

SHARED HUMAN-COMPUTER ALLOCATION

ALLOCATED TO HUMAN

ALLOCATED TO AUTOMATION

Figure 17 System Status Display: LSS Emergency Warning Procedure Checklist



-LOSS OF DESCENT POWER

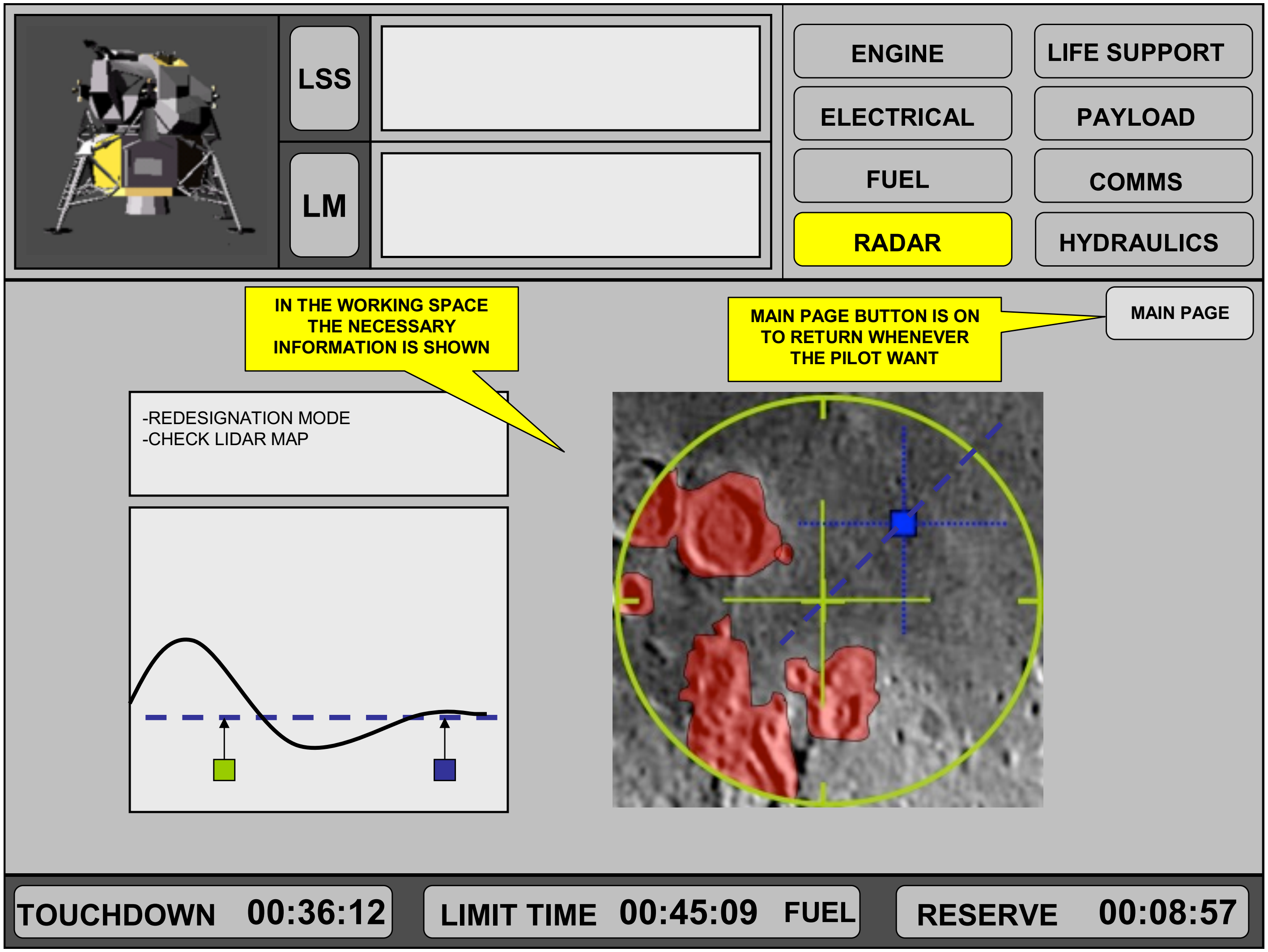
PROCEDURE:
PERFORM ARS PURGE

	AUTOMATIC	MANUAL
SWITCH SYSTEM ENGINEER BATTERY 5 ON	DONE	STOP DONE
SWITCH COMMANDER BATTERY 6 ON	DONE	STOP DONE
CLOSE DES 02 VALVE		DONE
CLOS	DONE	STOP DONE
SET WATER TANK SELECT VALVE TO	DONE	
CLOSE DES H2O VALVE	00:09	STOP DONE
RECONFIGURE ELECTRICAL LOADS AS REQUIRED		YES NO
PERFORM EPS BASIC (STAGED)		DONE

AUTOMATION COUNTS DOWN OR PILOT CAN TAKE CONTROL
Completed items turn grey (inactive)

TOUCHDOWN 00:36:12
LIMIT TIME 00:45:09
FUEL RESERVE 00:08:57

Figure 18 System Status Display: LM Emergency Warning Procedure Checklist



IN THE WORKING SPACE THE NECESSARY INFORMATION IS SHOWN

MAIN PAGE BUTTON IS ON TO RETURN WHENEVER THE PILOT WANT

-REDESIGNATION MODE
-CHECK LIDAR MAP

Figure 19 System Status Display: Master Caution

Appendix C Lunar Terrain Altitude Mapping: Past, Present, and Future Data

Information provided by: Ian Garrick-Bethell, iang@mit.edu
Summarized by Stephane Essama

Information Sorted by Missions:

- Pre-Apollo:
  - Ranger Program:
    - Crashed Cameras into Moon that captured images before impact.
    - Select areas of the Moon (about 10 sq km) were mapped at meter resolution.
  - Lunar Orbiters:
    - Mapped 95% of the moon photographically.
    - A lot was at scales of less than a meter (especially around equator)
    - Highest Resolution (< 100m) photos to date
      - Photographs are available in atlases, and online: http://www.lpi.usra.edu/resources/lunar_orbiter/ higher resolution for science use: http://cps.earth.northwestern.edu/LO/
- Apollo:
  - Regional geologic mapping.
  - CSM orbital photographs enhanced the mapping efforts at high resolution.
  - Mineralogical data.
  - Laser Range finder returns some medium quality data.

- Clementine (1994)
  - Global photographic coverage at 100-500 meter resolution.
  - Laser range finder offers global coverage at ~10 km resolution up to +/-70 deg latitude, vastly superior to Apollo era topography.
  - Mineralogical data.
  - Clementine global image map of the Moon is available online, at all five spectral bands, via the US Geological Survey. http://pdsmaps.wr.usgs.gov/PDS/public/explorer/html/moonpick.htm
  - The topography from the Clementine mission is available from NASA's planetary data service (geosciences node): http://pds-geosciences.wustl.edu/missions/clementine/index.htm

- Lunar Prospector (1998):
  - Mineralogical and Geological data.
  - All lunar prospector mission data is also available at the geosciences node:
    http://pds-geosciences.wustl.edu/missions/lunarp/index.htm

- Earth-Based Radar: (late 1990s)
    - Topographic maps of the poles were generated from measurements to ~600m resolution.

- SMART 1 (2003)
    - European Space Agency.
    - Camera System not much better than Clementine.
    - Will take first pictures of Southern Pole.

- Chandrayan (2007-2008):
    - Indian Mission for mineralogical characterization of the surface.
    - Imaging Mapper provided by Carle Pieters at Brown.

- Lunar Recon Orbiter (2008).
    - NASA mission
    - Very high resolution laser range finder.
    - Very high resolution camera.
    - Precision: within 50 m horizontally, and 1 m vertically.
    - Maria Zuber (MIT EAPS)

Combination of all these missions (especially Lunar Recon Orbiter, Clementine, Prospector, and Chandrayan should provide a great wealth of map-type knowledge).

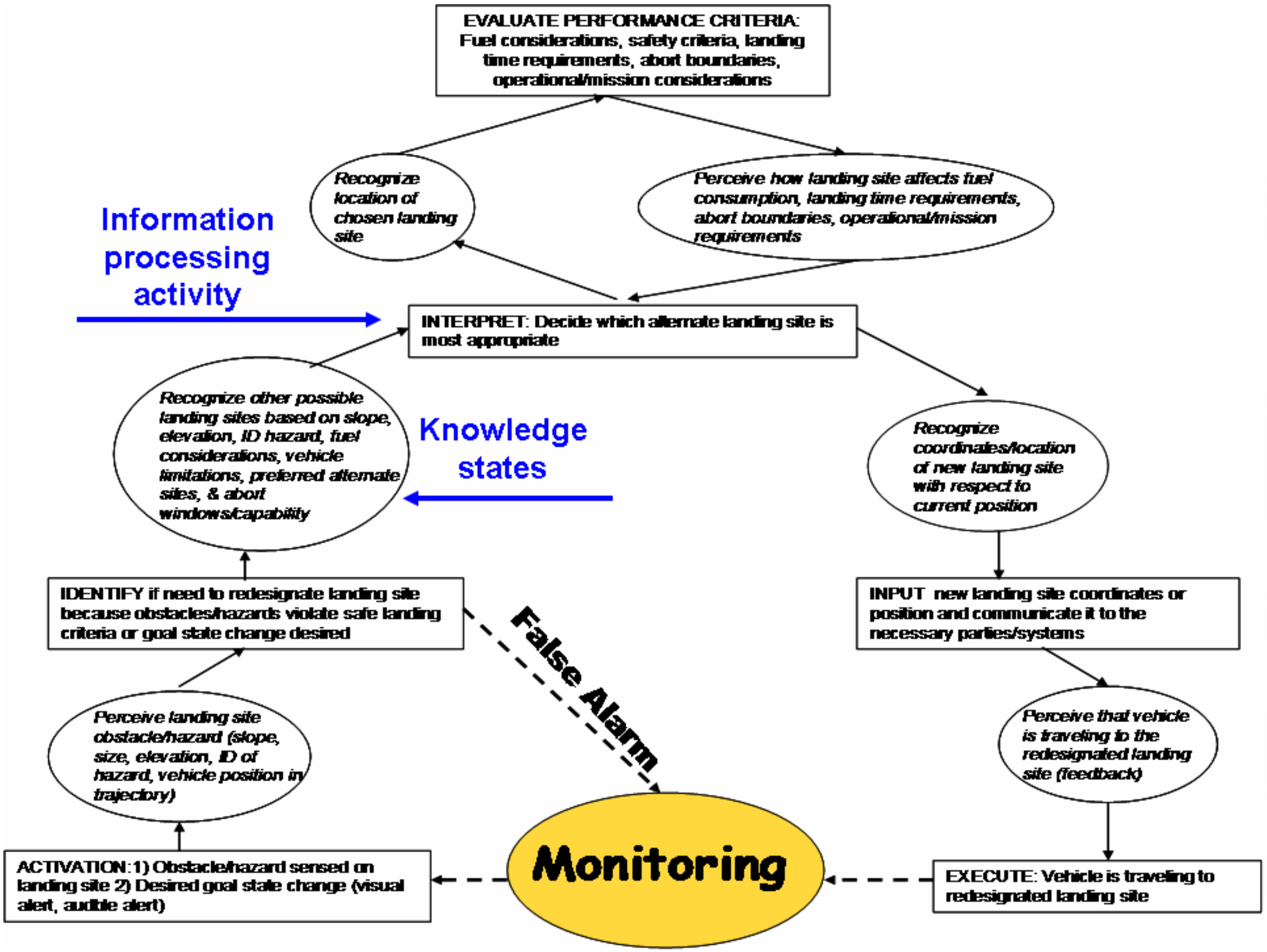
Appendix D Preliminary System Status Information Requirements

INFORMATION	ABORT CRITICAL	ACCEPTABLE WINDOW
Guidance System.		
Position	YES	Depends on Expected Values
X	YES	Depends on Expected Values
Y	YES	Depends on Expected Values
Z	YES	Depends on Expected Values
Velocity		
X	YES	Depends on Expected Values
Y	YES	Depends on Expected Values
Z	YES	Depends on Expected Values
Acceleration		
X	YES	Depends on Expected Values
Y	YES	Depends on Expected Values
Z	YES	Depends on Expected Values
Attitude		
Pitch	YES	Depends on Expected Values
Yaw	YES	Depends on Expected Values
Roll	YES	Depends on Expected Values
Rotation Rate		
Pitch	YES	Depends on Expected Values
Yaw	YES	Depends on Expected Values
Roll	YES	Depends on Expected Values
Rotation Accel.		
Pitch	YES	Depends on Expected Values
Yaw	YES	Depends on Expected Values
Roll	YES	Depends on Expected Values
Errors		
Position	YES	Depends on Expected Values
Velocity	YES	Depends on Expected Values
Rotation	YES	Depends on Expected Values
Rate	YES	Depends on Expected Values
Landing Site Area		
Position		
Elevation		
Obstacles		
Features		
Possible Landing Area	YES	Reachable
Desired vs Actual		
Position Change		
Land Site Selection		

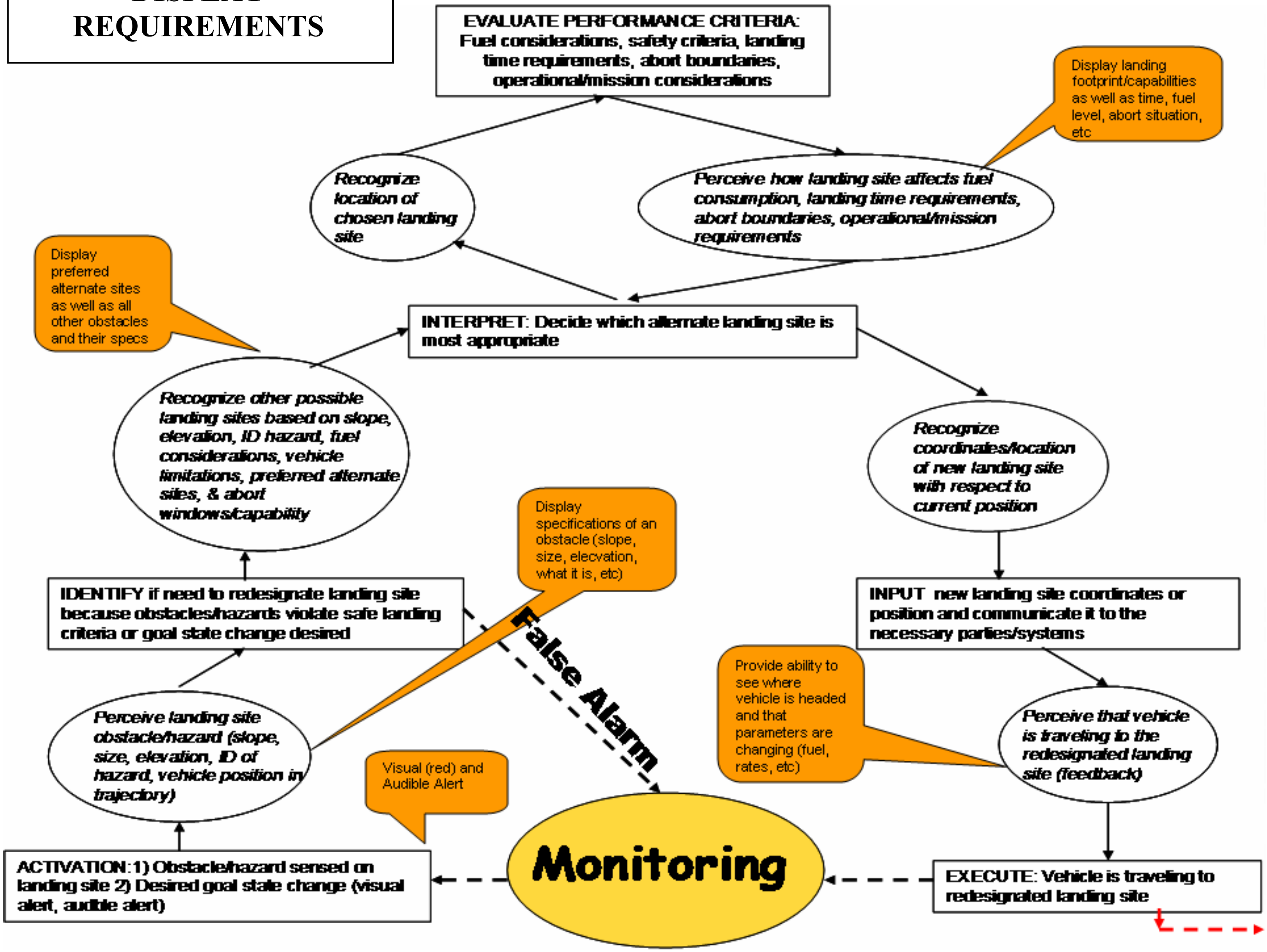
X,Y Changes		
Z Changes		
Backup system readiness	YES	Ready
Fuel		
Volume	YES	Depends on Expected Values
Time Left	YES	Depends on Expected Values
Warning	YES	If less than 20 secs away
Actual vs. Expected	YES	
Abort system readiness	YES	
Life support		
Oxygen		
Amount/Pressure	YES	19.5-23.1 kPa
Consumption Rate	YES	
Remaining Time	YES	Compare to Time till touchdown
CO2 Cleaning Rate	YES	Depends on number of crew.
Temperature	YES	18.3-26.7 deg C
Composition of Atmosphere	YES	78.3% N 21.7% O
Total Pressure	YES	99.9-102.7 kPa
Humidity	YES	(25-70%)
Water from fuel cells.	YES	
Power		
Remaining Time	YES	Compare to Time till touchdown
Distribution	YES	Functional
Warning	YES	Off
General Remaining Time	YES	Compare to Time till touchdown
Hardware		
Water coolant (for hardware)	YES	
Ventilation.	YES	Functional
Gas Containers	YES	No leaks
Waste Management/Engine leaks	YES	None
Manual Attitude Controller	YES	Functional
Sensor Status	YES	
Landing Radar	YES	Functional
Lidar	YES	Functional
Accelerometers	YES	Functional
Enhanced Vision Cameras.	YES	Functional
Overheating of Hardware	YES	Functional
Thruster Health	YES	Functional
Engine Health	YES	Functional
Hull health	YES	Functional

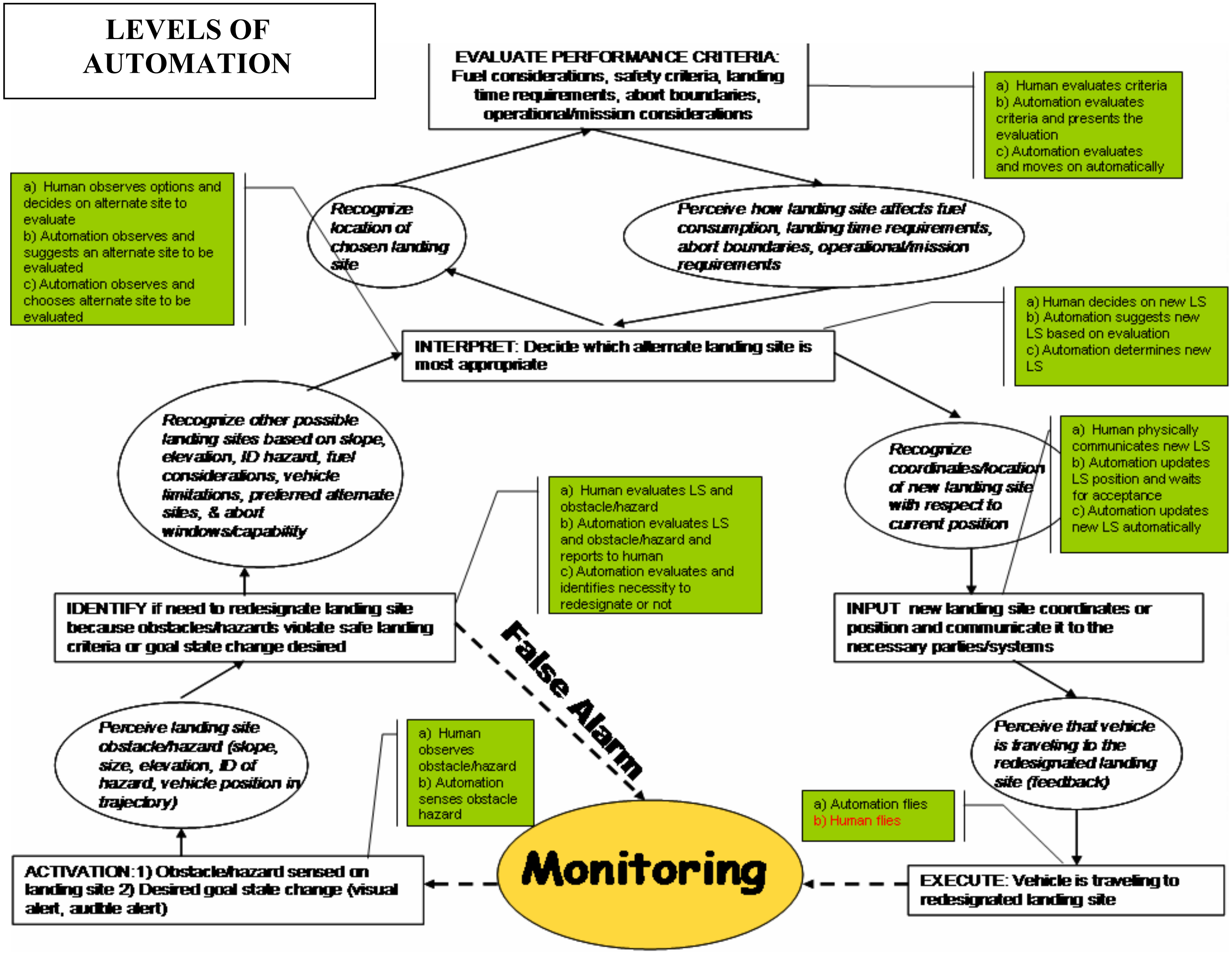
Appendix E Decision Ladders

LANDING SITE REDESIGNATION
Decision Ladder

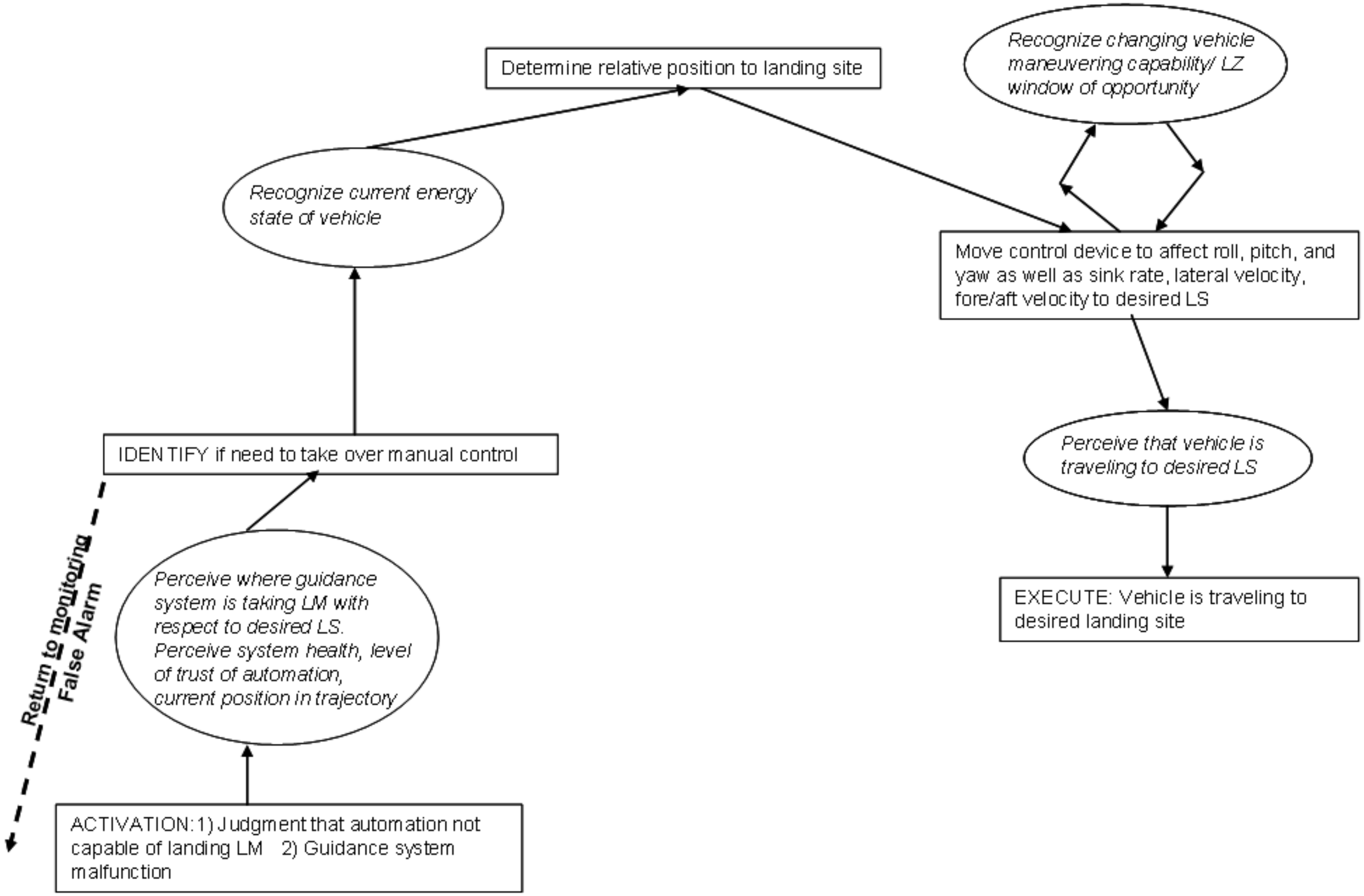

EVALUATE PERFORMANCE CRITERIA: Fuel considerations, safety criteria, landing time requirements, abort boundaries, operational/mission considerations
Recognize location of chosen landing site
Perceive how landing site affects fuel consumption, landing time requirements, abort boundaries, operational/mission requirements
Information processing activity
INTERPRET: Decide which alternate landing site is most appropriate
Recognize other possible landing sites based on slope, elevation, ID hazard, fuel considerations, vehicle limitations, preferred alternate sites, & abort windows/capability
Knowledge states
Recognize coordinates/location of new landing site with respect to current position
IDENTIFY if need to redesignate landing site because obstacles/hazards violate safe landing criteria or goal state change desired
False Alarm
INPUT new landing site coordinates or position and communicate it to the necessary parties/systems
Perceive landing site obstacle/hazard (slope, size, elevation, ID of hazard, vehicle position in trajectory)
Perceive that vehicle is traveling to the redesignated landing site (feedback)
Monitoring
ACTIVATION: 1) Obstacle/hazard sensed on landing site 2) Desired goal state change (visual alert, audible alert)
EXECUTE: Vehicle is traveling to redesignated landing site

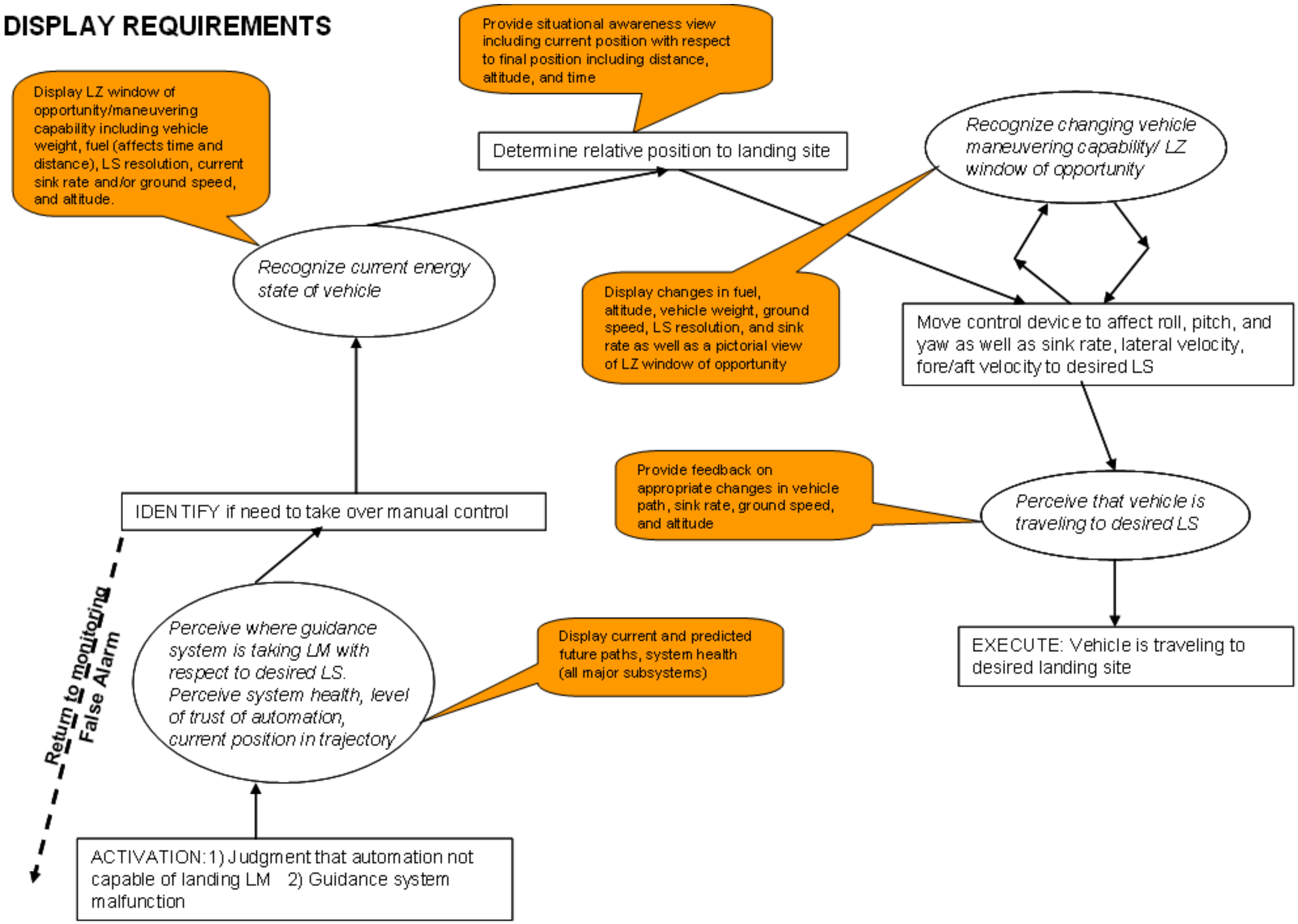
DISPLAY REQUIREMENTS



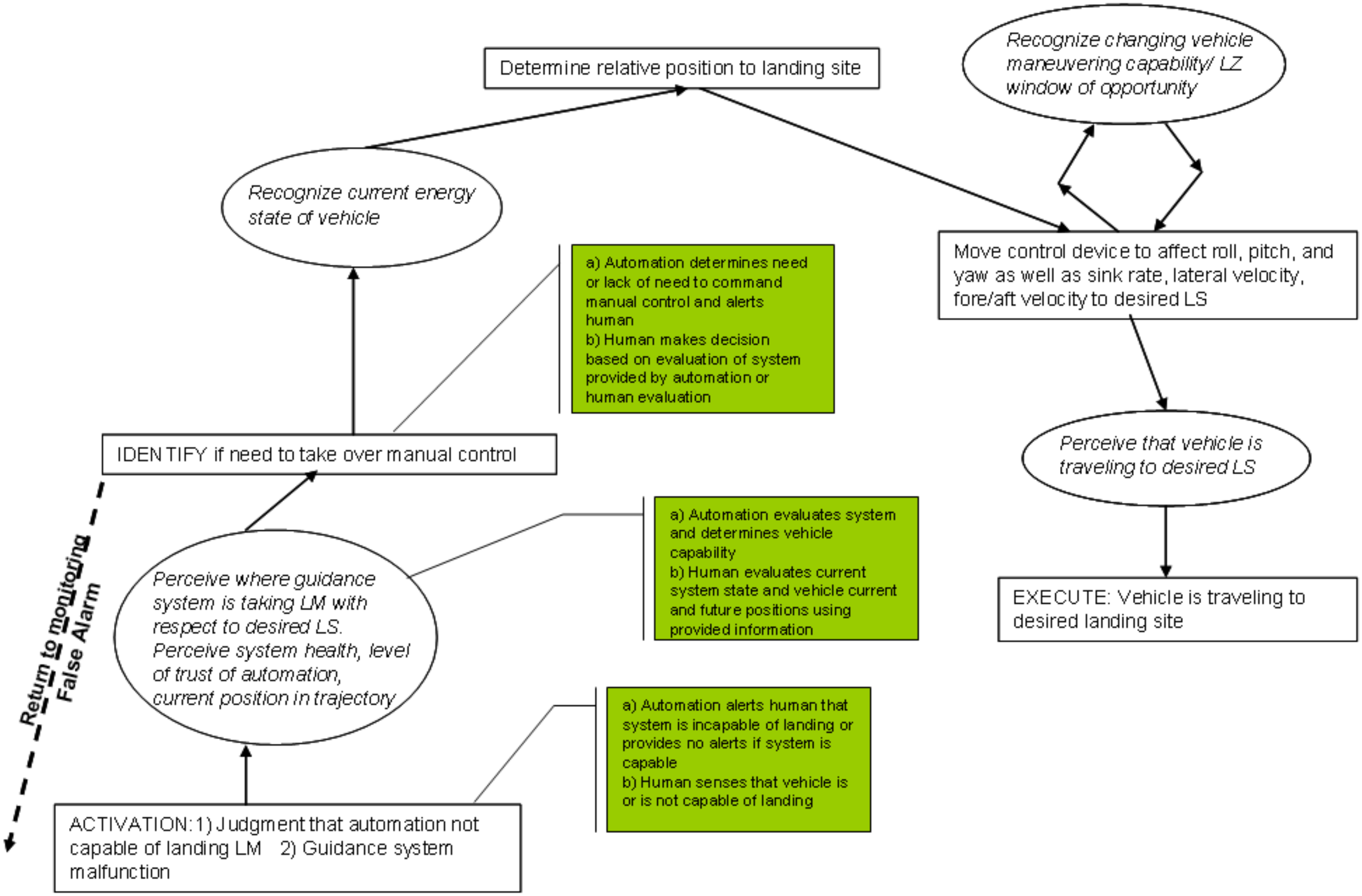

LEVELS OF AUTOMATION
EVALUATE PERFORMANCE CRITERIA: Fuel considerations, safety criteria, landing time requirements, abort boundaries, operational/mission considerations
a) Human evaluates criteria
b) Automation evaluates criteria and presents the evaluation
c) Automation evaluates and moves on automatically
a) Human observes options and decides on alternate site to evaluate
b) Automation observes and suggests an alternate site to be evaluated
c) Automation observes and chooses alternate site to be evaluated
Recognize location of chosen landing site
Perceive how landing site affects fuel consumption, landing time requirements, abort boundaries, operational/mission requirements
a) Human decides on new LS
b) Automation suggests new LS based on evaluation
c) Automation determines new LS
INTERPRET: Decide which alternate landing site is most appropriate
Recognize other possible landing sites based on slope, elevation, ID hazard, fuel considerations, vehicle limitations, preferred alternate sites, & abort windows/capability
Recognize coordinates/location of new landing site with respect to current position
a) Human physically communicates new LS
b) Automation updates LS position and waits for acceptance
c) Automation updates new LS automatically
a) Human evaluates LS and obstacle/hazard
b) Automation evaluates LS and obstacle/hazard and reports to human
c) Automation evaluates and identifies necessity to redesignate or not
IDENTIFY if need to redesignate landing site because obstacles/hazards violate safe landing criteria or goal state change desired
False Alarm
INPUT new landing site coordinates or position and communicate it to the necessary parties/systems
Perceive landing site obstacle/hazard (slope, size, elevation, ID of hazard, vehicle position in trajectory)
a) Human observes obstacle/hazard
b) Automation senses obstacle hazard
Perceive that vehicle is traveling to the redesignated landing site (feedback)
a) Automation flies
b) Human flies
Monitoring
ACTIVATION: 1) Obstacle/hazard sensed on landing site 2) Desired goal state change (visual alert, audible alert)
EXECUTE: Vehicle is traveling to redesignated landing site

MANUAL CONTROL
Decision Ladder


Determine relative position to landing site
Recognize changing vehicle maneuvering capability/ LZ window of opportunity
Recognize current energy state of vehicle
Move control device to affect roll, pitch, and yaw as well as sink rate, lateral velocity, fore/aft velocity to desired LS
IDENTIFY if need to take over manual control
Perceive that vehicle is traveling to desired LS
Return to monitoring
False Alarm
Perceive where guidance system is taking LM with respect to desired LS. Perceive system health, level of trust of automation, current position in trajectory
EXECUTE: Vehicle is traveling to desired landing site
ACTIVATION: 1) Judgment that automation not capable of landing LM 2) Guidance system malfunction


DISPLAY REQUIREMENTS
Display LZ window of opportunity/maneuvering capability including vehicle weight, fuel (affects time and distance), LS resolution, current sink rate and/or ground speed, and altitude.
Provide situational awareness view including current position with respect to final position including distance, altitude, and time
Determine relative position to landing site
Recognize changing vehicle maneuvering capability/ LZ window of opportunity
Recognize current energy state of vehicle
Display changes in fuel, altitude, vehicle weight, ground speed, LS resolution, and sink rate as well as a pictorial view of LZ window of opportunity
Move control device to affect roll, pitch, and yaw as well as sink rate, lateral velocity, fore/aft velocity to desired LS
Provide feedback on appropriate changes in vehicle path, sink rate, ground speed, and altitude
Perceive that vehicle is traveling to desired LS
IDENTIFY if need to take over manual control
EXECUTE: Vehicle is traveling to desired landing site
Return to monitoring
False Alarm
Perceive where guidance system is taking LM with respect to desired LS. Perceive system health, level of trust of automation, current position in trajectory
Display current and predicted future paths, system health (all major subsystems)
ACTIVATION: 1) Judgment that automation not capable of landing LM 2) Guidance system malfunction

LEVELS OF AUTOMATION



Appendix F Summary of Apollo Press Kits

Characteristics of Lunar Module:

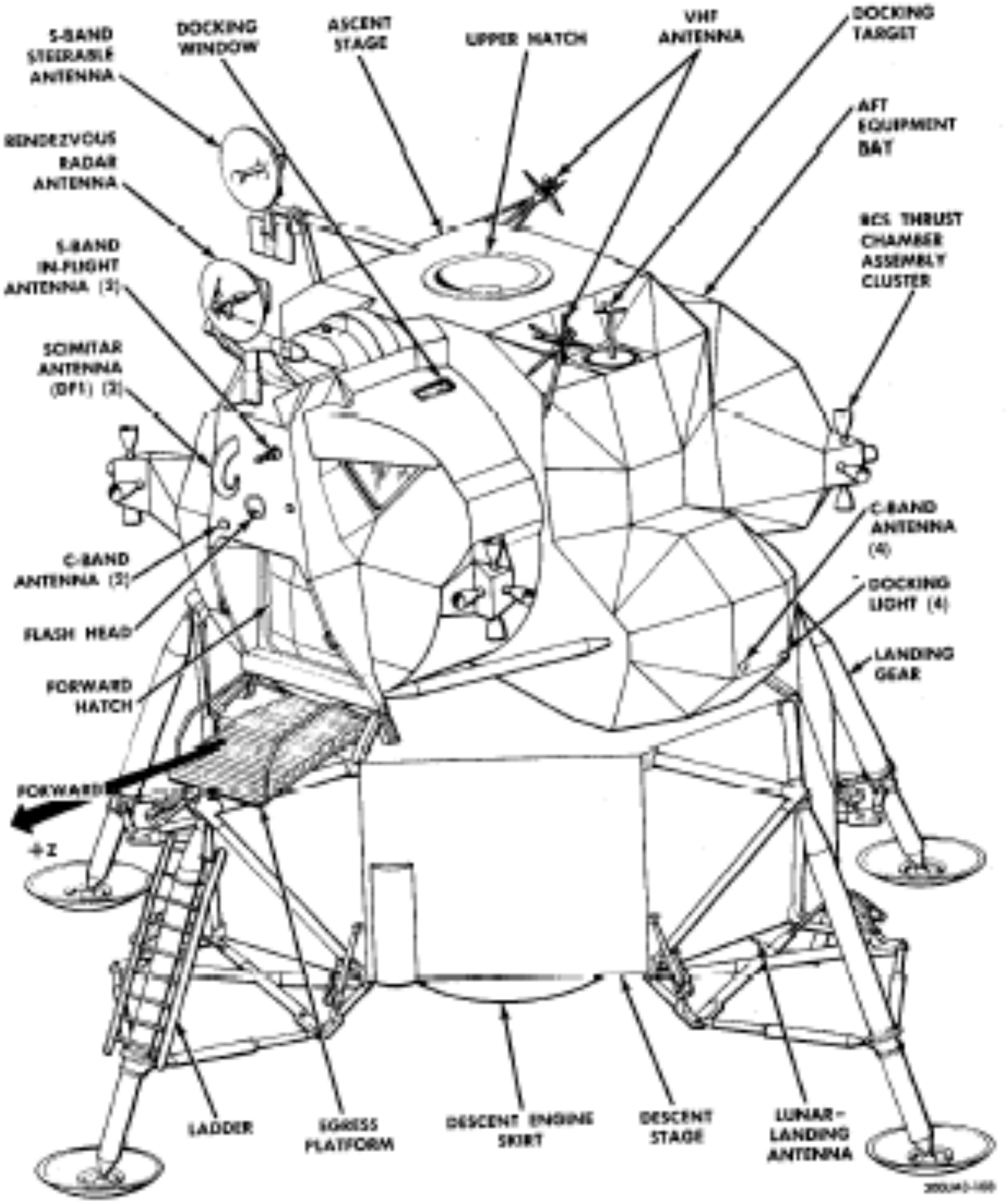
- Two separate parts joined by 4 explosive bolts and umbilicals: Ascent and Descent stage.
    - Ascent Stage: Three main sections, the crew compartment, midsection and aft equipment bay. LM guidance computer is located in midsection.

    - Descent Stage: Each pad is fitted with lunar-surface sensing probe which signal the crew to shut down the descent engine upon the contact with the lunar surface.

- LM-3 weighs 32021 pounds (Ascent stage: 5071, Descent stage: 4265, Propellants 22685)

- Computer Systems (relevant to landing and GN&C)
    - Communications system: Includes a UHF receiver that accepts command signals from ground control that are fed to the LM guidance Computer.
    - Guidance, Navigation and Control System: Comprised of six sections: **Primary Guidance and Navigation Section** (PGNS), **Abort Guidance Section** (AGS), Radar Section, Control Electronics Section (Lorenz), and Orbital Rate Drive Electronics for Apollo and LM (Ordeal).
        - PGNS: System composed of Alignment optical telescope, Inertial measurement unit and Radars (for landing and rendezvous). Provides inertial reference data, inertial alignment reference (with optical sighting data), displays position and velocity data, controls attitude and thrust to maintain desired LM trajectory and controls descent engine Throttling and Gimballing.
        - AGS: Independent backup system having its own inertial sensor and computer.
        - Radar: Feeds altitude and velocity data to the LM guidance computer.
        - CES: Controls attitude and translation about all axes. Controls automatic operation (ascent and descent engines, and reaction control thrusters) through PGNS , handles manual attitude controller and thrust-translation controller commands.
        - Ordeal: Displays pitch in orbit.
    - Abort system: When engaged, separates ascent stage from descent stage and guides LM to an abort orbit. In order to avoid accidental abortion, the system is engaged in four steps.
    - Caution and Warning System: Monitors spacecraft systems for out-of-tolerance conditions and alerts crew by visual and audible alarms so that crewmen may trouble-shoot the problem.

-43b-



-more-

Figure 1 Diagram of Lunar Module Systems (JONES,2000)

Landing Sequence[3]:

- LM separates from command module descends to an elliptical orbit with a low point of 50,000 feet. (This is when the descent starts)

- Descent Orbit Insertion burn (DOI) 74.2 fps. 10% throttle for the first 15 seconds then 40% throttle.

- Preparation of PDI.

    - Landing radar turned on.
    - Initialize AGS. Align the AGS with PGNS, the AGS will be updated regularly according to new developments.

- Powered Descent Initiation maneuver begins, uses Descent engine to break the vehicle out of the Descending orbit. Three Phases.
    - Guidance Controlled PDI maneuver begins 260 nm before touchdown. Retrograde attitude in order to reduce velocity to near 0 at the beginning of vertical descent.
        - They report velocity residuals (along X and Z axis) of onboard state vectors to ground control (as of Apollo 12) in order to get new coordinates for landing site.
        - Ullage
        - Ignition of Descent Engine.
        - Manual Throttle Up
        - Manual Target update (coordinates)
        - Check Radar Data
        - Throttle Down
        - Change Scale of Landing radar.
        - Braking Phase ends at 7000 feet altitude.

    - P64 Beginning of Approach Phase (named: High Gate) Approach Phase allows pilot take over manually. It also permits visual evaluations of landing site.
        - Start Pitchover at 4 degrees per second.
        - Landing radar antenna to Position 2.
        - Attitude Hold.
    - P66 Beginning of Landing Phase (named: Low Gate). Landing Phase allows pilot take over manually. It also permits visual evaluation of landing site.
    - Final Vertical Descent begins at 150 feet, after forward velocity is 0. Vertical descent rate= 3fps
- Touchdown.
    - Probe contacts lunar surface.
    - “Lunar contact” indicator lights up

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[3] Compiled by cross referencing event sequences for Apollo 11,12, and 14

- o After 1 second crew turns descent engine off.
- o LM settles on surface.

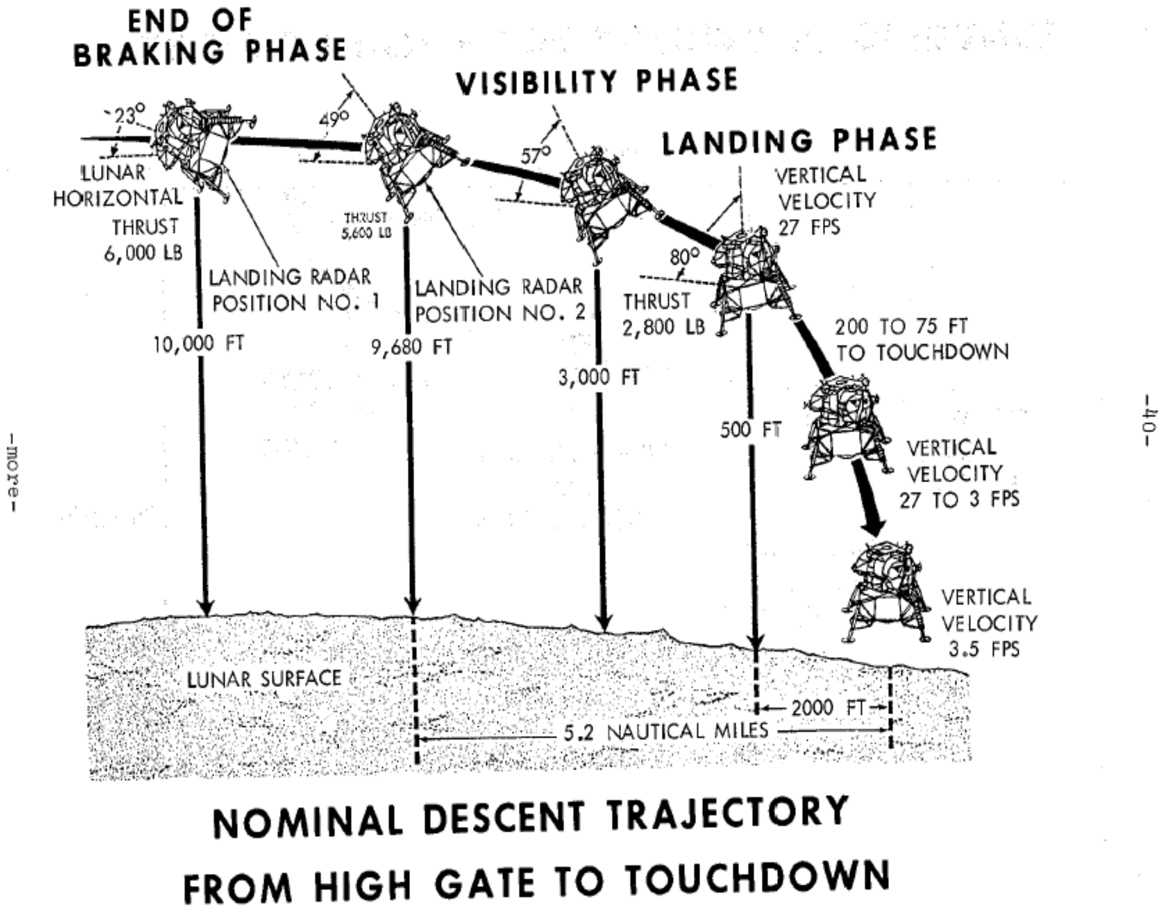


Figure 2 Descent Trajectory Apollo Lunar Lander

Differences between Missions:

- Apollo 11 and Apollo 12.
    - In Apollo 12, the LM undocks in the correct attitude (radically outward and therefore does not need to reorient itself).
    - Residuals are not trimmed but reported to ground control, which calculates a new vector and redesignates a new landing site.
    - No more pitch-attitude drift check (more precise one was performed before undocking).
    - More westerly landing site allowed more time for pilots and ground control to adjust in case of unpredicted conditions.
    - Ability to manually update new landing site coordinates in the program. Resulted in a correction of 4200 feet.

- Apollo 12 and Apollo 13.
    - Combination of LOI-2 and DOI conserves propellant for the PDI.

- Apollo 13 and Apollo 14.
    - Did not find any significant differences relevant to the Landing sequence. (repeat because of failure?)
- Apollo 14 and Apollo 15
    - Lunar Descent trajectory was 14 degrees for Apollo 14 and 25 degrees for Apollo 15. Results in:
        - Significant enhancement of terrain clearance.
        - Significant enhancement of visibility and fidelity of LPD.
        - No significant increase in vertical Velocity.
        - Modest increase in Delta-V for redesignations.

    - Changing the GET clock according to delays.
    - Changing from H mission to J mission (longer duration mission).
    - Additional consumables required for longer stay on the surface and additional propellant to enable landing a greater payload on the moon.

APPROACH PHASE COMPARISION

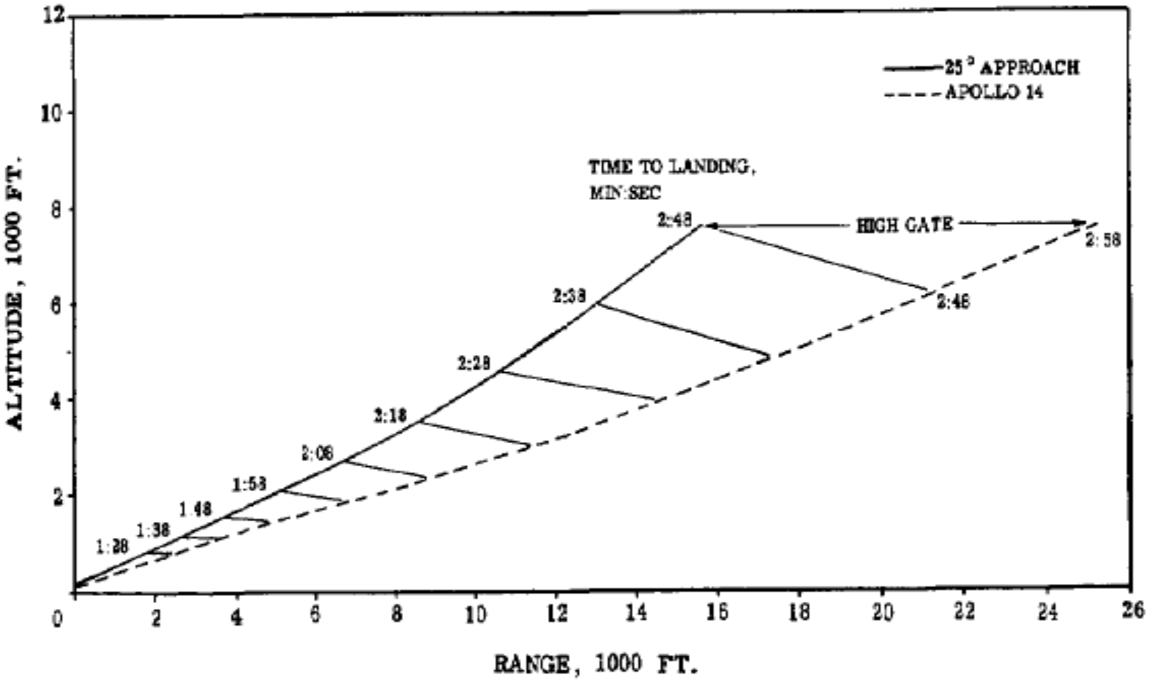


Figure 3 Approach Phase Comparisons

- Apollo 16, and 17.

  No significant difference was found in terms of landing sequence.

Example of the Sequence of commands given by the Pilots during the landing sequence Apollo 16 (Translated from DSKY entries):

- AGS Activation.
    - Monitor Command Module Computer Time.
    - Set AGS time using 90 hour Bias.
    - Run tests
        - Self Tests
        - Logic Test
        - Logic and Memory Test

- MSFN Update.
    - Copy AGS K-factor.
    - Set LM state vector into CSM state vector (??)
    - Load AGS K-factor update.

- Landing Radar Checkout.
    - Sample Radar once per second.
    - Call up Landing Radar slant range and Landing Radar Position.
    - Display distance to target (in .1 nm)
    - Terminate function.

- Crewman Optical Alignment Sight (COAS) alignment.
    - Call up data.
    - Call up Optical Calibration Data Display.

- Landing Point Designator (LPD) Calibration.
    - Call up data.
    - Call up Optical Calibration Data Display.

- Manned Space Flight Network (MSFN) update.

- Configure COMM for LOS.
    - Match Indicated Angles.

- MNVR to AGS CAL ATT.
    - Start crew defined MNVR

- AGS Calibration.
    - Monitor ICDU angles.
    - Set ICDU attitude equal to angles.

- CSM circularization:
    - Start orbit parameter display.

- P63 Ignition Algorithm Test.

    - Auto-maneuver Roll (0), Pitch (111), and Yaw (340).
    - Load Digital Autopilot.
    - Terminate Function.

- Pre-PDI switch setting check.
    - Commander uses Thrust/Translation Controller Assembly (TTCA) lower throttle to minimum.
    - Check Descent Propulsion System, Ascent Propulsion System, Reaction Control System, Environmental Control System,.

- AGS Initialize.
    - Set LM state Vector into CSM state vector.

- PDI
    - Engage P63
    - Load components (Beta, DL, and VL) in R1, R2, and R3 (couldn't find what those mean, am assuming Beta is an angle, and VL is some velocity).
    - Auto maneuver Roll, Pitch and Yaw (same values as before)
    - Final Trim (assuming: of residuals)
    - Engage P64
    - Ignite Engine
    - Throttle up
    - Load Bank Angle in R1
    - Load Bank Angle in R1. DL in R2
    - Engage P66
    - Display Bank Angle, Inertial Velocity, and Altitude Rate.
    - Touchdown
    - Engine Alarm- off.

Appendix G Apollo Landing Sequence Storyboard

The Apollo Landing Sequence Storyboard is an interactive power point show that details tasks and decisions within the various phases of the landing sequence. Below is the initial slide. Each red text links to other slide that describes the corresponding events. This twenty-five page document was utilized to understand the elements of the Apollo landing as well as provide insight as to the crew tasks. The main documents used to create this storyboard were: the Apollo Lunar Surface Journals (Jones 2005), Appendix F Summary of Apollo Press Kits.

Download Apollo Landing Sequence Storyboard:
http://web.mit.edu/aeroastro/www/labs/halab/lunar.html

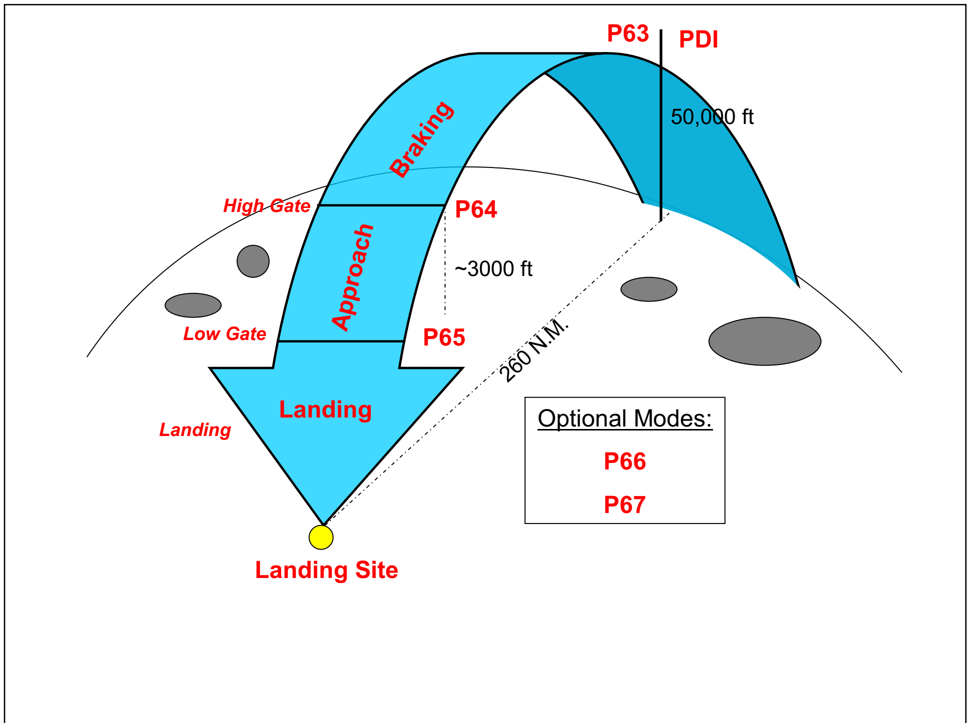


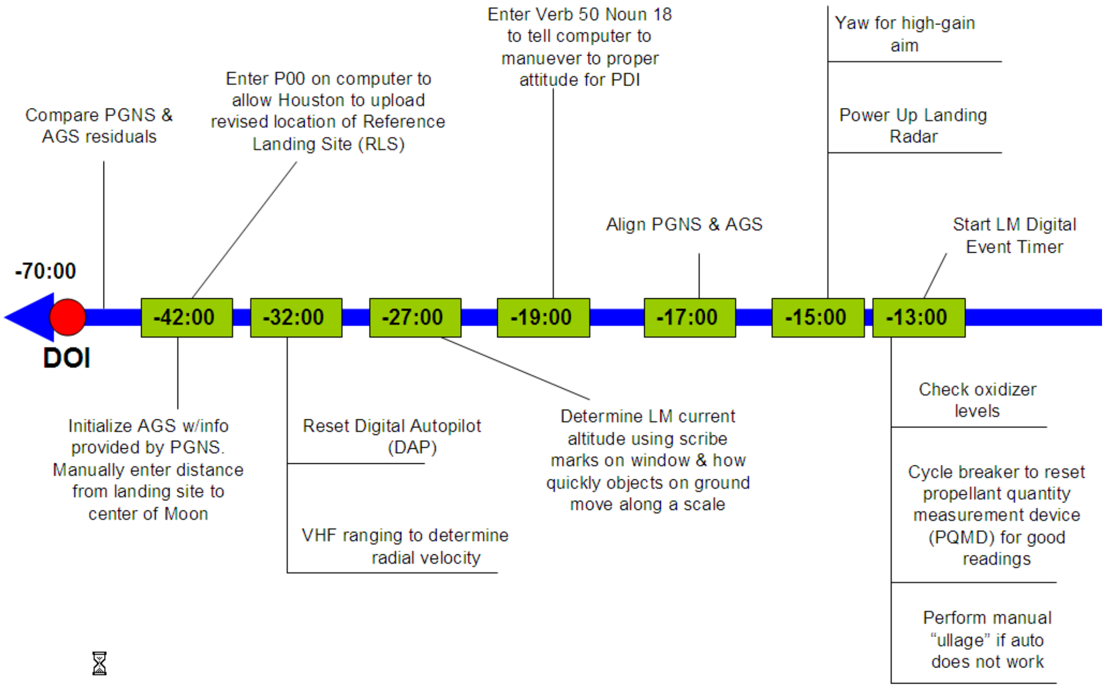
Figure 1 Screen Shot of Apollo Landing Sequence Storyboard

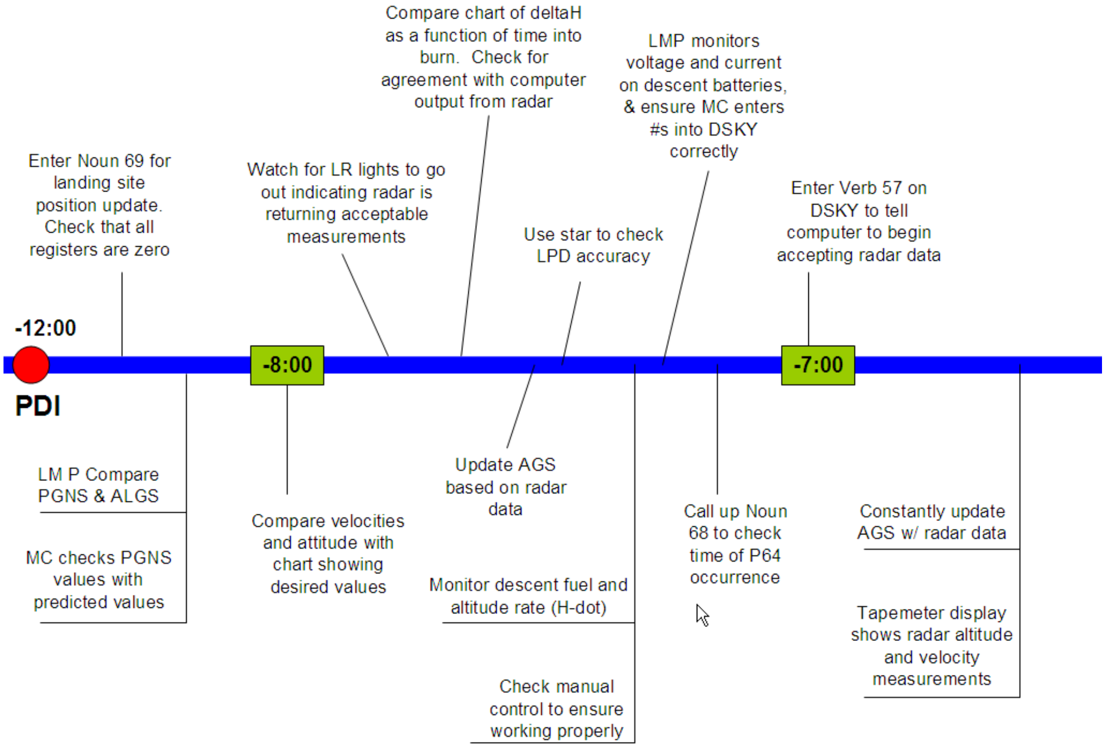
Reference

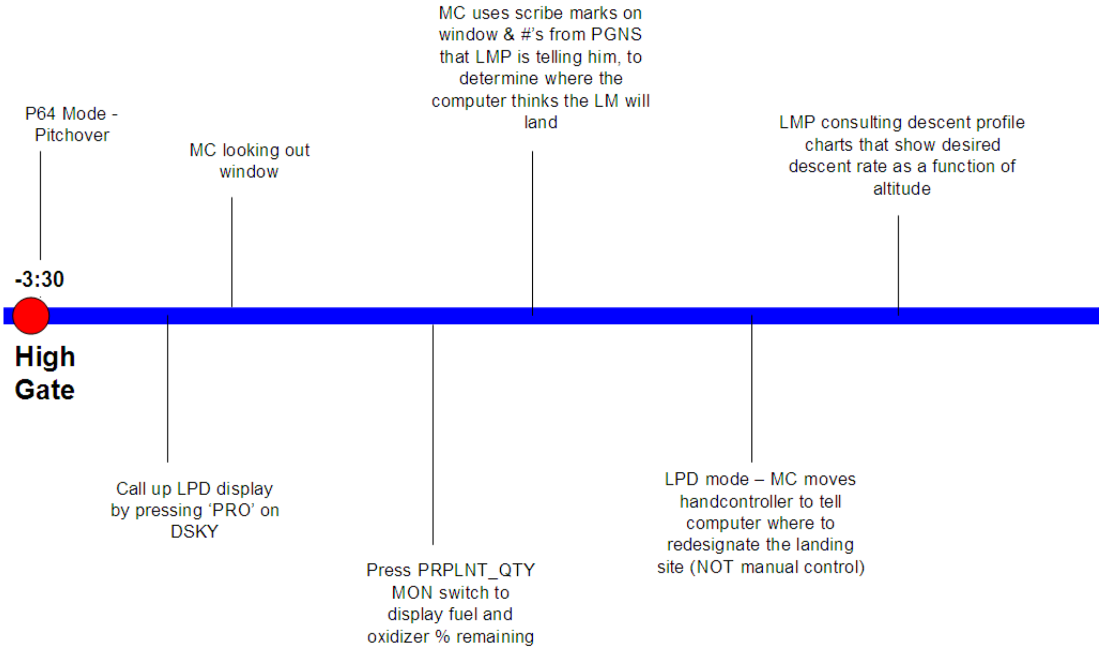
Jones, E. M. (2000). *Apollo Lunar Surface Journal*. Retrieved September, 2005, from http://www.hq.nasa.gov/office/pao/History/alsj/frame.html

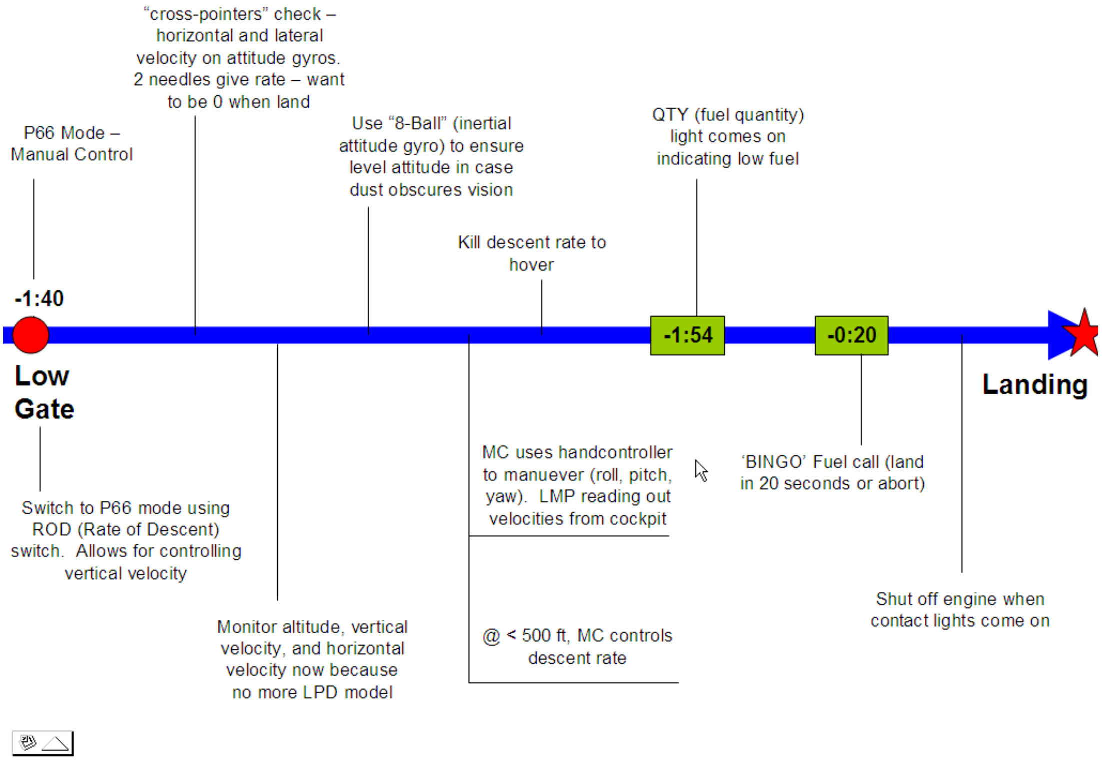
Appendix H Apollo Landing Timeline

The Apollo Landing Timeline is a summary of the times and events that occurred in the Moon landings. It is based on both the Apollo Landing Sequence Storyboard (developed by the human-system integration team) and the Apollo Lunar Surface Journals (Jones, 2000). The main purpose for this timeline was to provide a global understanding ("big picture") of major events and tasks the crew had to initiate during the landing sequence. Furthermore, this document was used to outline distinctions between automated and human-controlled tasks.




-12:00
PDI
-8:00
-7:00
Enter Noun 69 for landing site position update. Check that all registers are zero
Watch for LR lights to go out indicating radar is returning acceptable measurements
Compare chart of deltaH as a function of time into burn. Check for agreement with computer output from radar
Use star to check LPD accuracy
LMP monitors voltage and current on descent batteries, & ensure MC enters #s into DSKY correctly
Enter Verb 57 on DSKY to tell computer to begin accepting radar data
LM P Compare PGNS & ALGS
MC checks PGNS values with predicted values
Compare velocities and attitude with chart showing desired values
Update AGS based on radar data
Monitor descent fuel and altitude rate (H-dot)
Check manual control to ensure working properly
Call up Noun 68 to check time of P64 occurrence
Constantly update AGS w/ radar data
Tapemeter display shows radar altitude and velocity measurements


P64 Mode - Pitchover
-3:30
High Gate
MC looking out window
MC uses scribe marks on window & #'s from PGNS that LMP is telling him, to determine where the computer thinks the LM will land
LMP consulting descent profile charts that show desired descent rate as a function of altitude
Call up LPD display by pressing 'PRO' on DSKY
Press PRPLNT_QTY MON switch to display fuel and oxidizer % remaining
LPD mode – MC moves handcontroller to tell computer where to redesignate the landing site (NOT manual control)



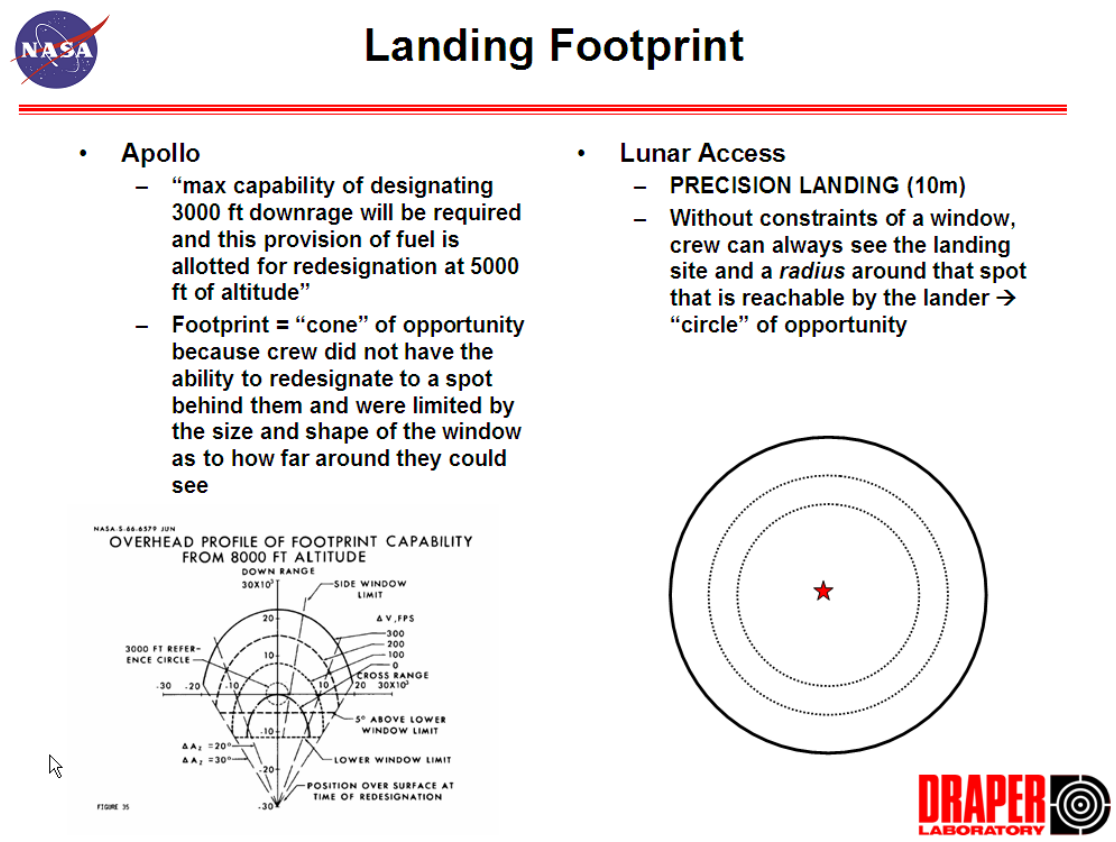
Reference

Jones, E. M. (2000). *Apollo Lunar Surface Journal*. Retrieved September, 2005, from http://www.hq.nasa.gov/office/pao/History/alsj/frame.html.

Appendix I Landing on the Moon: Comparison between Apollo-era and Lunar Access Project

The “Landing on the Moon: Comparison between Apollo-era and Lunar Access Project” is a comprehensive assessment of the different constraints that drove the Apollo Lunar Lander design and the expected equivalence for the Lunar Access Project. The focus was on multiple elements that specifically dealt with trajectory and human-driven requirements. For example, Apollo’s redesignation ability was constrained to the window size while the Lunar Access Project does not limit itself to this. Below is a screen shot of another example, the landing footprint.

Download “Landing on the Moon: Comparison between Apollo-era and Lunar Access Project”: http://web.mit.edu/aeroastro/www/labs/halab/lunar.html



Landing Footprint

- Apollo
  - “max capability of designating 3000 ft downrage will be required and this provision of fuel is allotted for redesignation at 5000 ft of altitude”
  - Footprint = “cone” of opportunity because crew did not have the ability to redesignate to a spot behind them and were limited by the size and shape of the window as to how far around they could see
- Lunar Access
  - PRECISION LANDING (10m)
  - Without constraints of a window, crew can always see the landing site and a *radius* around that spot that is reachable by the lander → “circle” of opportunity

Figure 1 "Landing on the Moon: Comparison between Apollo-era and Lunar Access Project", Screen Shot

Appendix J Acronyms and Abbreviations

3D	Three dimensional
AGS	Abort Guidance Section
ApLL	Apollo lunar lander
ATT	Attitude
CAL	Calibration
CAU	Cockpit Avionics Upgrade (Space Shuttle)
CES	Control Electronic System
CMDR	Commander
COAS	Crewman Optical Alignment Sight
COMM	Communications
CSM	Command and Service Module
DOI	Descent Orbit Insertion
DSKY	Display and Keyboard Assembly
GET	Ground Elapsed Time
GN & C	Guidance, Navigation, and Control
HITL	Human-in-the-loop
H-SI	Human-System Interface
IFR	Instrument Flight Rules
KBB	Knowledge-Based Behavior
LAV	Lunar Access Vehicle
LIDAR	Light Detection and Ranging
LLTV	Lunar Lander Training Vehicle
LM	Lunar Module
LMP	Lunar Modal Pilot
LOI	Lunar Orbit Insertion
LOS	Loss Of Site
LPD	Landing Point Designation
LSS	Life Support System
LZ	Landing Zone
MSFN	Manned Space Flight Network
NASA	National Aeronautics and Space Agency
PDI	Power Descent Insertion
PGNS	Primary Guidance and Navigation Section
PP	Procedure Panel
RBB	Rule-Based Behavior
SA	Situational Awareness
SAE	Society of Automotive Engineers
SAP	Status Alert Panel

SBB	Skill-Based Behavior
SS	System Status
TTCA	Thrust/Translation Controller Assembly
TTO	Technology, Tasks, and Operators
UHF	Ultra High Frequency
VAVI	Vertical Altitude and Velocity Indicator
VTOL	Vertical Take-off and Landing