Human Lunar Landing Experience On Project Apollo

How We Did It
Why We Did It That Way
Conclusions and Implications for Human Landing System Design

31 December 2019
Dean Eppler
The Aerospace Corporation
dean.b.eppler@aero.org
dean.b.eppler@SanAntonioMountainConsulting.com

Presentation Sections

- Introduction
- Basic terminology and acronyms
- Apollo approach to lunar landing – Basic Approach
- Primary Lunar Module Systems
    - Descent Propulsion System
    - LM Reaction Control System
    - LM Landing Radar
    - Primary and Abort Guidance System ("Pings and Ags")
    - Lunar Module Guidance Computer
    - Cockpit controls
    - LM Commander's Window
    - CDR and LMP
- Apollo approach to lunar landing – the actual implementation
    - Spacecraft elements – which vehicle is doing which task and why?
    - Aborts and Abort Modes
    - Site selection constraints
    - How we flew the approach
- Apollo landing crew experience – how did it come off for real?
    - Apollo 11 – Getting it on the ground in one piece and coming home
    - Apollo 12 – Precision landing in "relatively" benign terrain
    - Apollo 14 – Precision landing in more challenging terrain
    - Apollo 15, 16 and 17 – Landing in the mountains on the Moon
- Conclusions and Implications for future Human Landing System (HLS) design
- Source Listing

Introduction

Study Background and Purpose

- This study was undertaken largely because in the 4-5 decades since the end of the Apollo Program, the detailed methodology and history of how we landed on the Moon has been largely lost from NASA's institutional memory

- This has led to many misconceptions and confusion, including:
  - The flight crew did all the flying
  - The flight crew did none of the flying
  - The Lunar Module Pilot was flying the LM
  - The Lunar Module Pilot wasn't doing anything at all*
  - The Commander was flying the LM
  - The ground was flying the LM
  - The computer was flying the LM

- This history has significant relevance for the preliminary development of the Artemis human lander
  - The teams selected by NASA for the Artemis lander are in the process of making critical, up-front engineering decisions that cannot be easily, or cheaply, "undone" later if they prove to be incorrect

- If we're going to go back to the Moon, we need to understand how we got there in the first place, including what worked, what didn't, how we did things, and who was doing them

*Note the following comment from Donald Wilhelms 1993 memoir titled, "To A Rocky Moon": "….[on Apollo 8] no LM was ready for Anders to fly (not that the LMP actually piloted the LM anyway).."

A Disclaimer and Acknowledgements

- Understanding how Apollo landed on the Moon is like peeling an increasingly complex onion
  - There are (still) several levels of complexity below what I was able to ferret out or report on for this presentation and this report is a ***significant*** simplification of an ***extremely*** complex process
    - *"The lunar landing was a very complex series of maneuvers, including subtleties and 2nd order effects that have not really been published (as far as I know)."* [Dave Scott, e-mail to Eppler, 2 January 2020]
  - However, I believe the more detailed layers are about implementation, not about the high-level approaches to landing on the Moon; consequently, I think these conclusions will be valid for initial Artemis definition

- The number of people we can ask directly, "How did you land on the Moon?" is diminishing all the time, and like all history, it's getting harder to nail down questions that should have been asked years ago…
  - Several folks have expressed dismay we didn't capture as much knowledge from Apollo as we should have, but the key information that is often missing is "assumed knowledge"…the everyday information that people shared and didn't think to define in memos, during space-to-ground conversations and in debriefs
    - Think of it this way – if you got hit by a bus on the way to work tomorrow, would someone that didn't have a background in your part of the space business understand everything you did just by reading your e-mails, files and reports?
  - The fact is that NASA did an excellent job of capturing the experience of Apollo, largely in the form of 130 individual documents called "Apollo Experience Reports", covering everything from LM landing techniques to space suit engineering and procurement to food

A Disclaimer and Acknowledgements

- This work benefitted greatly from discussions and critiques by many folks, including Anthony Ceccacci, Gerry Griffin, Jeff Hanley, Frank O'Brien, Harrison Schmitt, David R. Scott and David Woods

- ***<u>HOWEVER…any flaws, misconceptions, incorrectly filled-in blanks and wrong conclusions should be pointed out to me with no reservations</u>*** – it's the only way we'll get this story straight and be able to influence the next generation of lunar landers and the crewmembers, engineers and operators who will develop them and fly them

Critical Sources

- I will include a more complete reference list at the end, but a few sources need to be called out up front, as they were critical to understanding what we did 50+ years ago

- First, the Apollo Lunar Surface Journal and its companion source, the Apollo Flight Journal, continue to be the go-to place for any information about detailed, minute-by-minute transcripts and for interpretations by crewmembers and very talented auxiliary contributors to the journal
  - Throughout this report, the use of italics denotes a direct quote, either from the ALSJ or other sources

- Second, David Mindell's "Digital Apollo" is the best source of both how we did the Apollo human-machine interface, as well as a great discussion of how flying in the atmosphere and, by evolution, flying in space changed from the pre-World War II era all the way forward through Apollo into the Space Shuttle era – everyone in this business should read this book!

Sources (cont.)

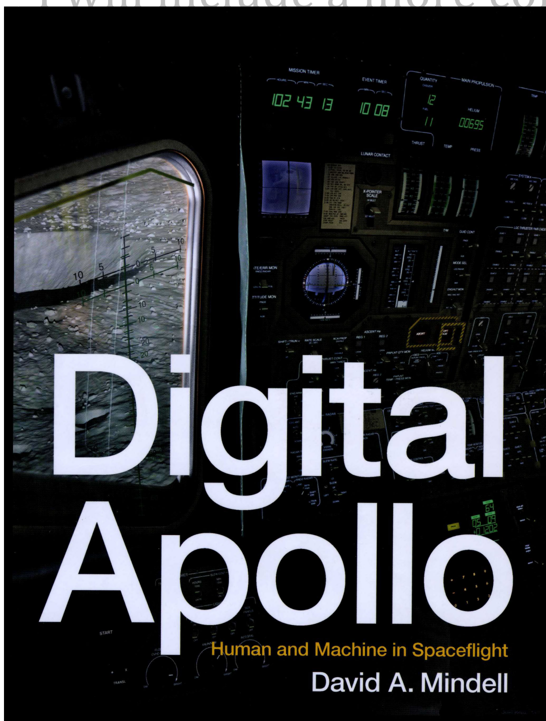
- Third, Don Eyles' "Sunburst and Luminary: An Apollo Memoir" captures how the computer code for Apollo was both conceived, written (and in some cases, *rewritten during flight*) and implemented (hint – if you read Mindell's and Eyles book in parallel, you get a great view of two sides of the coin on software development)

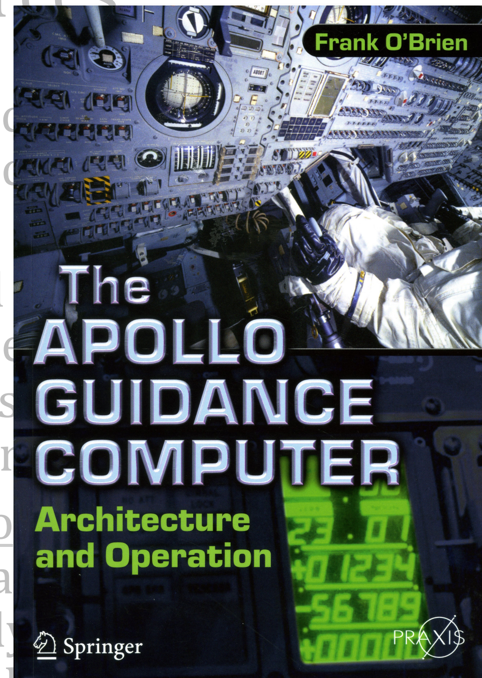
- Fourth, Frank O'Brien's "The Apollo Guidance Computer: Execution and Operation" is the most complete compilation of data on the LM guidance computer and its software out there.

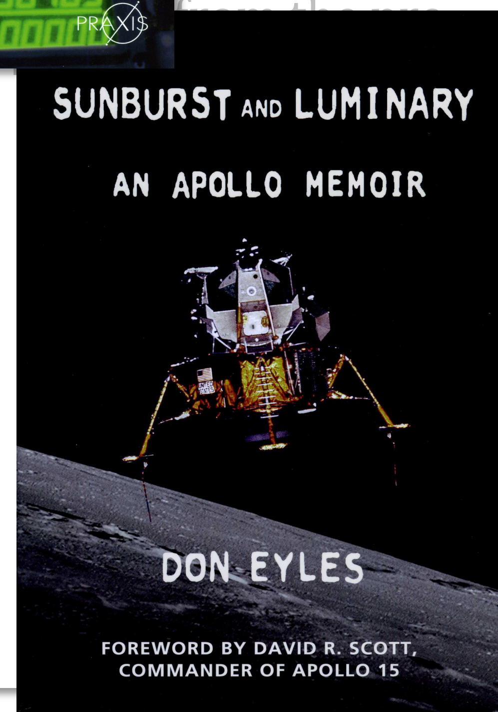
- Lastly, the post-flight crew debriefs are critical in understanding how the crew remembered, immediately post flight, their experience landing the LM and, when combined with the transcripts from the ALSJ and other sources, allows another dimension to be added to this activity
  - These can be found, along with a host of other sources, on the ALSJ

Sources

- I will include a more complete referenc … few sources need
  …, as they were c … ng what we did
- …urface Journal … rce, the Apollo
  …tinued to be the … formation about
  …ute transcripts … y crewmembers
  …ary contributor
- … “Digital Apollo … both how we did
  …ine interface, a … ssion of how flying
  …by evolution, fly
  … way forward th … ra
- … w
  the computer … s,
  rewritten duri … es
  book in parall
  development)
- Third, the pos … w
  remembered,
  when combin
  another dimen







PDI to Touchdown Videos

- The Apollo Flight Journal has put together a set of videos that combine the crew air-to-ground with the CAPCOMM and PAO loop from just prior to the start of Powered Descent through to touchdown
  - Apollo 11, PDI to touchdown (note: updated version from David Woods which includes the Flight Director loop as well as the crew voice loop) https://history.nasa.gov/afj/ap11fj/10day3-flight-plan-update.html#0581404
  - Apollo 12, PDI to touchdown: https://www.youtube.com/watch?v=kFSa6vUix70
  - Apollo 14, PDI to touchdown: https://www.youtube.com/watch?v=oZZe-xXx9_o
  - Apollo 15, PDI to touchdown: https://www.youtube.com/watch?v=AxqKlDsgMzc&t=7s
  - Apollo 16, PDI to touchdown: https://www.youtube.com/watch?v=JSXhb3J05ps&t=3s
  - Apollo 17, PDI to touchdown: https://www.youtube.com/watch?v=A7y5feeMvEo&t=869s

- Watching each of these is time well spent, if only to hear the interaction in the LM cockpit, as well as between the LM and the ground

A Brief Note on Units of Measurement

- Apollo did its planning at time when NASA was initially using a variety of units, including aviation units (knots, nautical miles), English units and metric units
    - However, early in the 1970s, the Agency decided to standardize to all metric units
- Remarkably, this never caused a technical hiccup in any operation, but it did result in a plethora of units being used for different phases of flight
    - For instance, orbital velocities were often called out in feet per second (abbreviated here ft s^{-1}), but orbital altitudes were often designated in nautical miles and EVA distances on the surface were called out in kilometers
- For the purposes of consistencies with historical documents, and because this report largely covers orbital operations down to a surface landing, I'm going to stick with the units used in those documents rather than convert units or list joint units (e.g., feet (km))
- I hope this does not confuse anyone unduly…

Basic Terminology and Acronyms

- **State Vector** – In simplest terms, it gives the position of the spacecraft in 3 numbers and the velocity in 3 numbers, with the added 7^{th} number the time at which the state vector was determined; in short, it's where the spacecraft is and how fast it's going in which direction at a discrete time

- **Descent Propulsion System (DPS, or "Dips")** – the rocket engine in the descent stage that allowed the LM to descend from orbit to the Moon

- **Ascent Propulsion System (APS)** – the rocket engine that either took the crew off the Moon under a nominal mission, or allowed the LM to abort from various points of during descent and get back up to orbit for an eventual rendezvous with the Command-Service Module

- **Landing Radar (LR)** – the continuous-wave radar system that provided the Lunar Module Guidance Computer (LGC) with radar altitude and altitude rate information, which was used by the guidance computer to calculate range and rate to the target point

Basic Terminology and Acronyms

- **Primary Guidance and Navigation Control System (PGNCS, or “Pings”)** – The Inertial Measuring Units (IMUs, which included gyroscopes and accelerometers), computers, I/O devices and software that allowed the crew to operate both the LM and the CSM; the heart of the system –IMU – is often referred to simply as “the platform”

- **Abort Guidance System (AGS, or “Ags”)** – The secondary system of gyroscopes, computers, I/O devices and software that backed up the PGNCS and would allow the crew to fly in the event of a total PGNCS failure

- **LM Guidance Computer (LGC)** –The computer on board the LM that took inputs from the on-board IMU, the crew and the ground and executed specific programs that controlled the LM main propulsion system and Reaction Control System to execute a particular phase of a landing, abort or ascent

- **Display-Keyboard (DSKY, pronounced as “Diskee”)** – the computer interface in both the LM and CSM that allowed the crew to input data, receive data, or initiate a particular flight phase

Basic Terminology and Acronyms

- **LGC Programs (also referred to with by their “P” numbers, such as “P63”)** – Specific loaded programs within the LGC that would execute a defined set of maneuvers to complete a particular flight phase; the first number of a particular program was generic for a given flight phase (e.g., in the LGC, all P6X numbers dealt with lunar landing)

- **LGC Verbs (identified with specific numbers, such as Verb 37)** – Specific actions that told the computer what to do; e.g., Verb 37 told the LGC to standby for new program initiation instructions

- **LGC Nouns (identified with specific numbers, such as Noun 33)** – Instructions to the LGC to display specific data on the DSKY, such as time to engine ignition for a given flight phase, or input data, such as the angular position of navigational fixes

Basic Terminology and Acronyms (cont.)

- **Landing Phase** – the particular segment of a lunar landing that involved a specific set of vehicle actions designed to place the LM on the lunar surface

- $\mathbf{T_{IG}}$ – Time of ignition for a particular burn; often called out as "Tig" or "Delta Tig" in burn residual reports

- $\mathbf{T_{GO}}$ – Time to Go until the start of a particular landing phase; sometimes called out as T_{TG}

- **H** - Symbol for altitude above the lunar surface

- **H-dot** – Symbol for altitude change rate

- **LOS/AOS** – Loss/acquisition of LM data when the LM either went behind the Moon (LOS) or came in sight of the Earth after a far side pass (AOS)

- **Ullage burn –** A brief burn of the LM Reaction Control System (RCS) prior to the initiation of powered descent insertion, performed to position the LM fuel and oxidizer to the bottom of the prop/oxidizer tanks; often referred to by the crew as just, "Ullage."

How To Land on the Moon – The Basics

Apollo Lunar Approach and Landing – Basic Approach

- There are two approaches to landing on any planet – a direct descent from the inbound trajectory without going into an initial parking orbit, or a descent from a parking orbit
  - The Surveyor robotic landers used the direct descent approach, which works well as long as the descent procedure was nominal
  - However, if there was a major propulsion anomaly, there was very little chance for recovery from a catastrophic surface impact
    - In fact, Surveyors II and IV were likely lost in this manner

- Apollo chose the latter approach, starting with the Command-Service Module (CSM)/Lunar Module (LM) stack going into an ≈60 nautical mile (nm) circular parking orbit

- The problem of getting safely to the lunar surface was then broken into four segments by one of the Space Task Group members named Donald Cheatham
  - Phase 1: Get the LM into an new orbit to set up the descent to the surface
  - Phase 2: Put the LM in a continuous braking trajectory to get it near the surface
  - Phase 3: Put the LM in a final approach trajectory to the planned landing site
  - Phase 4: Land

Apollo Lunar Approach and Landing – Basic Approach

- Phase 1: Put the LM into an elliptical orbit (called the descent orbit) using a minimum energy Hohmann transfer orbit burn (called the Descent Orbit Insertion burn or DOI burn) with an apoapsis of ≈60 nm and a periapsis of ≈50,000 ft that was ≈250 nm up range from the landing site,

- Phase 2: The Braking Phase
  - At the periapsis of the Descent Orbit, the Descent Propulsion System (DPS) would be ignited to put the spacecraft on a trajectory to both reduce altitude and velocity, bring it to an altitude and location from which the final landing approach and touchdown would be made
  - This maneuver was called "Powered Descent"
    - It lasted 8-9 minutes and took the vehicle from ≈50,000 ft and ≈5,500 ft s^{-1} horizontal velocity at Powered Descent Insertion (PDI) to a point ≈7,000 ft above the lunar surface and ≈700 ft s^{-1} vertical velocity (called High Gate)
    - During most of the Braking Phase, the LM would be flying engine bell/crewmember feet forward, "eyeballs up" with a largely horizontal thrust vector, giving the crew limited view of the lunar surface
    - The only change to the procedure was on Apollo 11, which flew the early portion of the powered descent "eyeballs down" so the crew could get time hacks on when particular points on the lunar surface flew by

Apollo Lunar Approach and Landing – Basic Approach

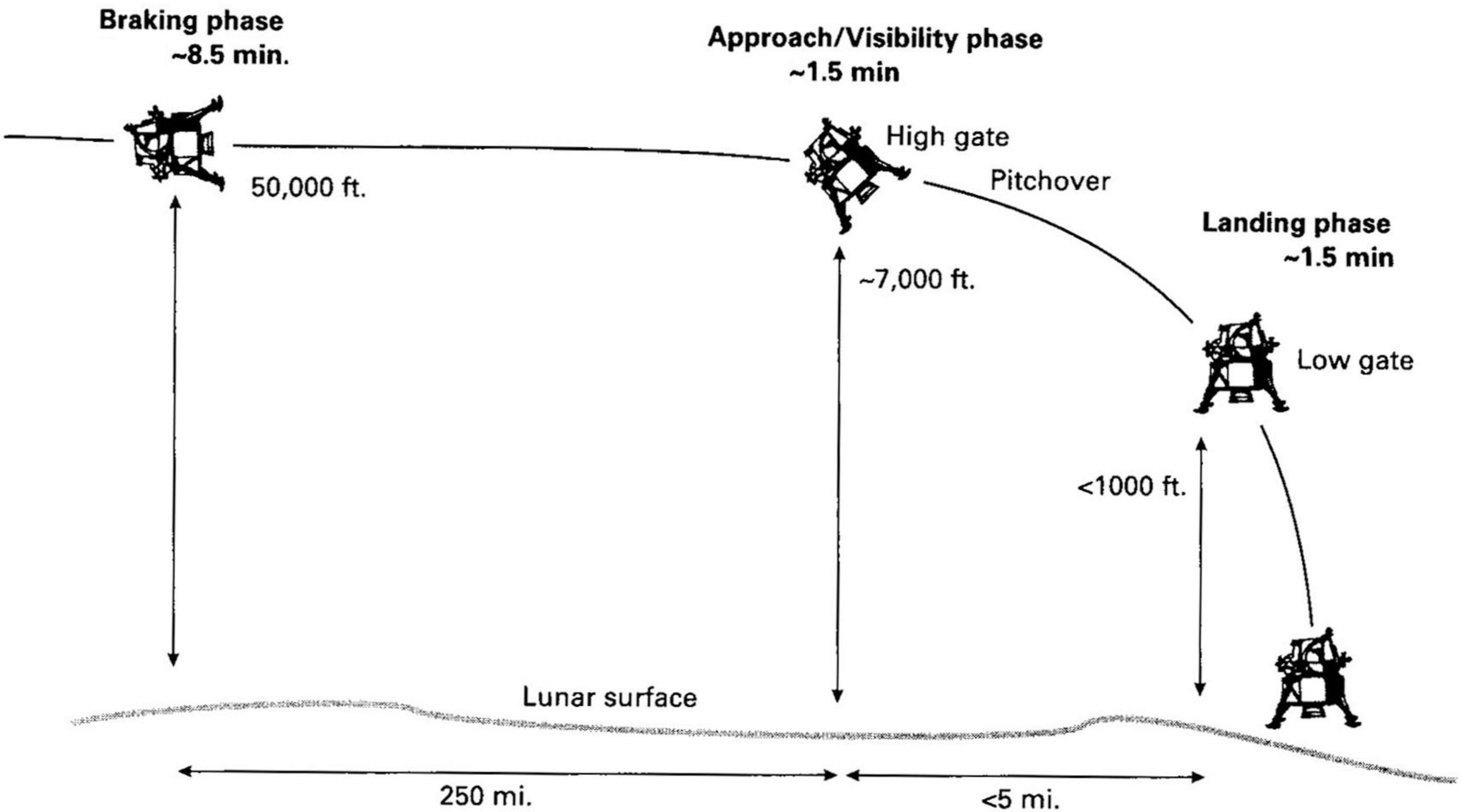
- Phase 3: The Approach/Visibility Phase (starting at High Gate)
    - Although the altitude at High Gate varied, it was usually between 5,000 and 8,000 ft AGL
    - At this point, the LM rotates about the pitch axis (called the pitchover maneuver), giving the DPS thrust vector a significant vertical component and allowing the crew to see the surface on which they would be landing, and enabling them to manage the touch down point of the LM

- Phase 4: The Landing Phase (starting at Low Gate)
    - This phase began at <1,000 ft AGL
    - At this point, the LM is in a largely vertical attitude, giving the DPS a primarily vertical thrust vector
    - Changing the LM attitude in pitch and roll would allow the crew to change the DPS thrust vector, thereby changing their predicted touchdown point while still continuing the descent
    - In addition, the engine could be throttled up or down, allowing the crew to manage descent rate

- This basic approach was used for each of the lunar landings
    - The details of these phases were worked out by a group in the Mission Planning and Analysis Division (MPAD) under Floyd V. Bennett

Apollo Lunar Approach and Landing – Basic Approach*

Figure 8.3 scanned from David Mindell, Digital Apollo.



Apollo Lunar Approach and Landing – Basic Approach*

*Figure created by Steve Tellier, retired LPI librarian

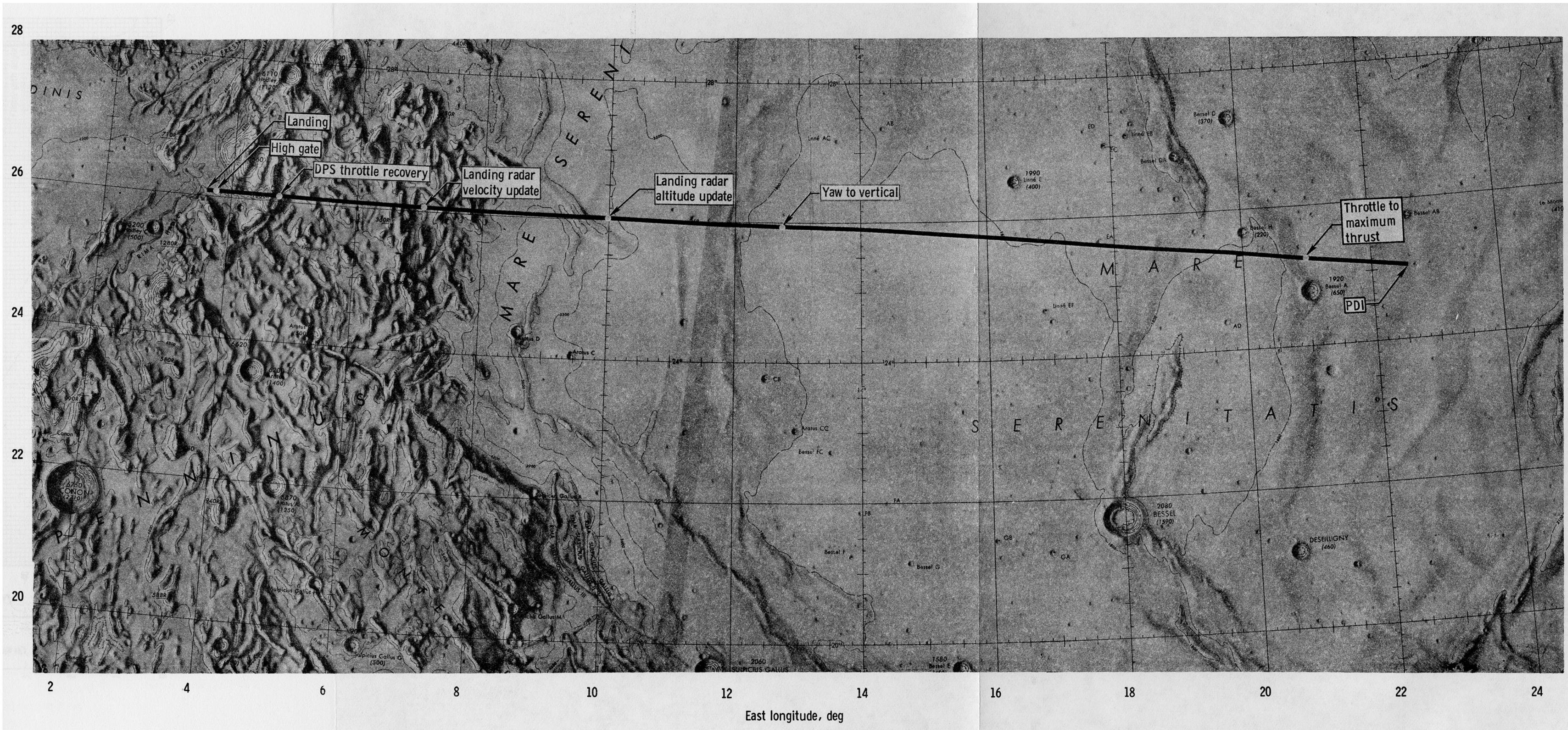


Figure 4.10-2.- LM powered descent groundtrack.

Apollo 15 ground track from powered descent insertion to landing

Primary LM Systems

Apollo Lunar Approach and Landing – LM Systems

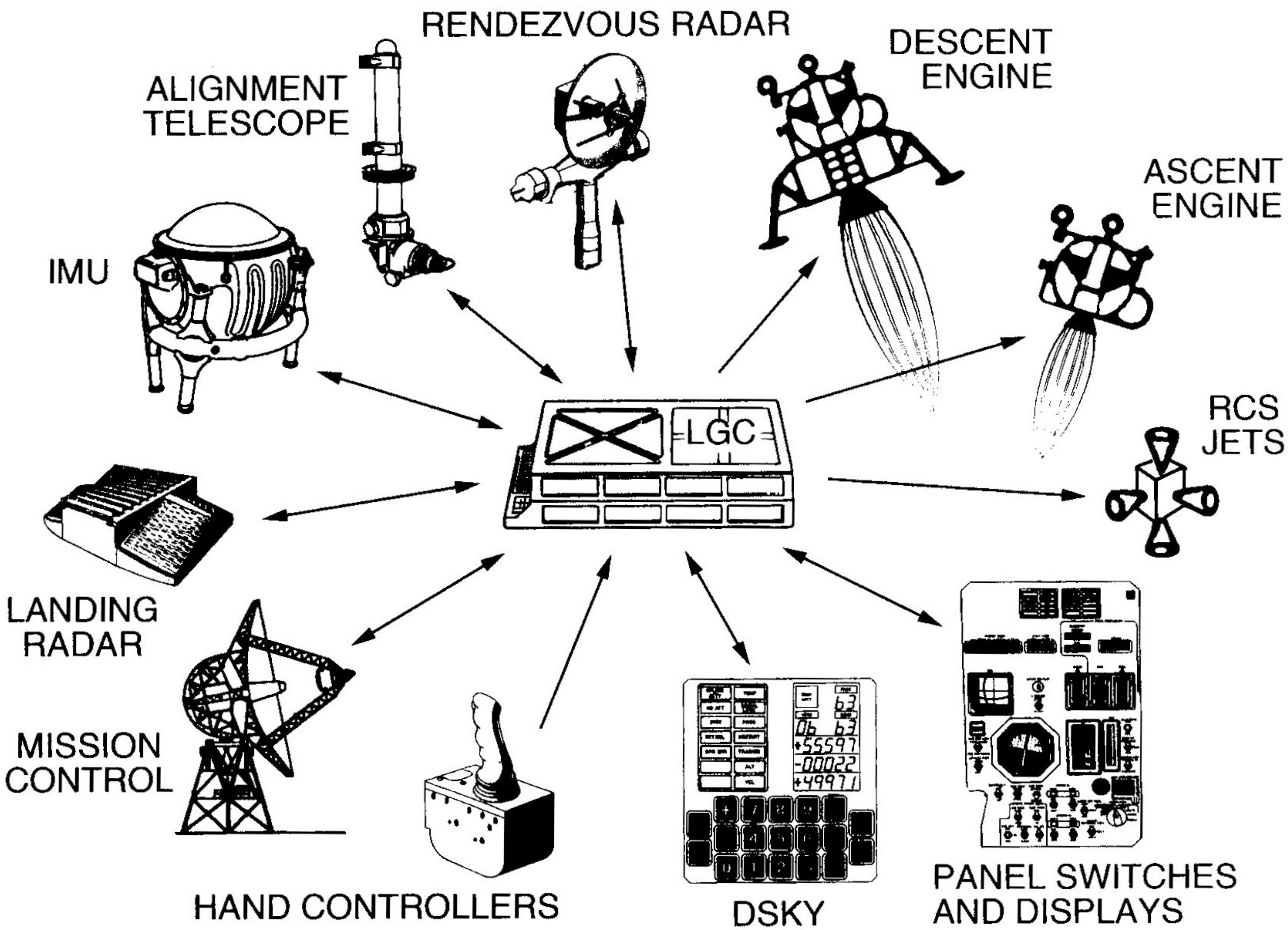
- The LM was a classical system-of-systems, each system having a different purpose, but each dependent on interaction with other systems to carry out the aggregate task of landing on the lunar surface

- The key LM systems discussed here will be as follows:
  - The LM Descent Propulsion System (DPS)
  - The LM Reaction Control System (RCS)
  - The Landing Radar (LR)
  - The Primary and Abort Guidance Systems (PNGCS ("Pings") and AGS)
  - The Lunar Module Guidance Computer (LGC), including the input hardware and software
  - The cockpit controls
  - The LM Commander's window
  - The Commander (CDR) and the Lunar Module Pilot (LMP)

- These elements formed a tightly knit interactive system that allowed us to safely land on the lunar surface six times, and bring the crew home safely each time

Apollo Lunar Approach and Landing – LM Systems*

*Note: Figure scanned from Don Eyles, Sunburst and Luminary, pg. 71.



Apollo Lunar Approach and Landing – LM Systems

- LM Descent Propulsion System (DPS)
  - The DPS was a throttleable hypergolic engine with an in-space restart capability
    - I_{sp} – 311 seconds
    - Thrust in vacuum – 10,125 lbf
    - Engine dry weight – 394 pounds
    - Fuel/Oxidizer – Aerozine 50/Nitrogen tetroxide
    - Throttle capability – 10% - 60%, and ≈90% - 100%
      - Engine nozzle erosion issues limited continuous operation between ≈60% and ≈90%
    - Pressure fed with supercritical He
  - The DPS was the first throttleable rocket engine developed, and it was an absolute necessity for landing on the lunar surface
  - Depending on the abort mode, DPS could be also be used for the initial stages of a aborted landing to get back to orbit
  - Engine bell extension modification on the Block II LM allowed an increase in engine performance and increased down mass for the Apollo J-missions

Apollo Lunar Approach and Landing – LM Systems

- LM Reaction Control System (RCS)
  - The LM RCS was a series of 16 thrusters mounted at four corners of the Ascent Stage that allowed rotation of the vehicle, initiated the pre-Powered Descent ullage burn and were part of the contingency Ascent Stage impulsive thrust in the event of an under-performing ascent engine
    - This was a hot-gas system, so LM structure had to be protected from RCS burn-through by providing plume deflectors and limiting firing durations
  - The RCS was a hypergolic system capable of multiple firings throughout the descent, landing, ascent and CSM rendezvous
    - Fuel/Oxidizer – Aerozine 50/Nitrogen tetroxide
    - Pressure fed with gaseous He
    - The RCS had two independent control and plumbing systems to provide redundancy
    - Typical performance during a mission was >1,000 seconds operating time and >10,000 firings
  - The RCS had three firing modes:
    - Direct crew firing using the translational (TTCA) and rotational (ACA) hand controllers, with no guidance computer input – essentially "hand flying"
    - Guidance computer-modulated firing in response to crew a single "pulse" of the rotation hand controller during the Approach and Landing Phases
    - Independent guidance computer firing to manage dynamic disturbances to the LM (primarily fuel sloshing) during the Approach and Landing Phases
  - In addition to the firing modes, the crew could select two dead band modes (±5°, ±20°) that would define how far out of a selected attitude the LM could rotate before the system would automatically fire to adjust back to the original attitude

Apollo Lunar Approach and Landing – LM Systems

- LM Landing Radar
  - The LM Landing Radar was a multi-beam radar system that provided slant range distance to the landing site using a 3-beam Doppler radar system, and altitude using a single beam vertical radar
  - Radar data was provided to the LM guidance computer to provide near-real time altitude (H), altitude rate (H-dot), and range to touch down
    - The derived H and H-dot was critical throughout the landing approach
      - LGC used a "spherical Moon model" that couldn't take into account detailed topography, meaning errors in calculated H and H-dot could be significant if not corrected by Landing Radar data
      - In addition, the lunar surface did not provide good visual cues that allow pilots to judge the height above the touchdown point and the range/range rate to the touchdown point, so radar data was essential to judging the landing
        - A cratered and ridged surface looks much the same from 10'000 ft as it does from 100 ft, making the normal altitude cues pilots use during terrestrial flight ops invalid
      - However, ***if*** H was <1,000 ft and a radar failure occurred, and flight rules did allow the crew to choose to land without radar data ***if*** there was good PGNCS and AGS data
  - Consequently, lack of Landing Radar data, or a significant lack of confidence in that data, triggered a mandatory abort for all the Apollo landings
    - Before the radar acquired the surface, two lights on the the computer interface (the DSKY) – the Altitude and Velocity Lights – remained illuminated, meaning radar data was not useable
    - Once good data was coming in, these lights went out, which was a key call during Powered Descent
    - Once the Altitude/Velocity lights were out, the crew and the ground had to assess the data using a routine within landing program P63 called "Delta-H", and manually tell the LGC, "This data is good, start using it."

Apollo Lunar Approach and Landing – LM Systems

- LM Landing Radar
  - The radar was located on the aft port underside of the descent stage, allowing the antennas to see the surface throughout the landing approach
  - The attitude of the LM during Powered Descent and some of the yaw maneuvers during that phase were designed to give the radar a good view of the surface
  - System weight – 42 pounds
  - System power consumption - ≈130 W
  - Altitude precision
    - >2,500’ - ±20’
    - <2,500’ - ±4’

Apollo Lunar Approach and Landing – LM Systems

- Primary Guidance and Navigation Control System (PGNCS, or "Pings")
  - To quote Frank O'Brien, "Alone by itself, the computer is blind to the world around it, lacking the most basic information on orientation and the accelerations the spacecraft undergoes (from, "The Apollo Guidance Computer")"
  - The PNGCS consisted of:
    - An inertial measuring unit (IMU) (AKA, the platform) with a 3-axis gyroscope to establish a stable platform, and accelerometers in each axis to measure vehicle acceleration during dynamic maneuvers
    - An optical observation system, connected to the LGC, that allowed the crew to determine the LM attitude with reference to a number of guide stars or lunar landmarks
      - Although the optical interfaces on the LM were different the CSM, the PNGCS in both vehicles were identical
    - A mechanical interface that connected the PGNCS rigidly to the LM structure
    - Electronic interfaces that allowed Landing Radar data to be fed directly into the PGNCS
  - These elements allowed the LGC to know where it was in inertial space, how it was moving, and allowed calculation of the appropriate DPS/RCS burns for landing on the lunar surface, initiating a nominal return to the CSM, or aborting back to the CSM
  - Several of the key, mandatory abort flight rules during LM descent and landing covered failures of the PNGCS, or failure of the PGNCS to agree with input data from the Landing Radar

Apollo Lunar Approach and Landing – LM Systems

- Abort Guidance System, or AGS
  - The AGS was designed to be able to provide backup navigational data to the LGC in the event of a total PGNCS failure during descent and landing
    - The name is a little confusing in that the "abort" referred to is NOT a landing abort, it's a failure of the PNGCS
      - An abort of a landing because of a DPS failure, with no concomitant failure of the PGNCS, would still be flown with PGNCS data
      - However, an abort initiated because of a total PGNCS failure *would* be flown on the AGS
  - The AGS used a strapdown IMU, as opposed to the gimbaled system in PGNCS, and Landing Radar data was not fed into the AGS
    - It had a separate computer (the abort electronics assembly (AEA) and display unit/ keyboard (the Data Entry and Display Assembly, or DEDA)) mounted on the LMP side of the cockpit
    - It also had a separate system of software commands that had to be entered by the LMP at a number of times during the LM descent and landing
  - Although the AGS had a lower degree of precision, it was continually used to check the health and quality of PNGCS data
    - The call by the LMP, "Pings and Ags agree" was often heard during lunar descent
  - The crews came to trust the AGS as much as the PGNCS, particularly for it's ability to keep up with the LM as it flew the approach
    - In various debriefs, Gene Cernan commented that if they'd lost the PNGCS after High Gate, he felt the AGS provided good enough data to be able to land with only AGS data

Apollo Lunar Approach and Landing – LM Systems

- The Lunar Module Guidance Computer was a early digital computer that provided computational capability and guidance, navigation and control interfaces to the LM systems during descent, landing and ascent, acting as a digital autopilot
  - The LGC was designed at the MIT Instrumentation Laboratory under Charles Stark Draper, with hardware design led by Eldon C. Hall
  - Early architectural work came from J. Hal Laning Jr., Albert Hopkins, Richard Battin, Ramon Alonso, Hugh Blair-Smith and Herb Taylor
  - Programming for the LM landing was largely done by Don Eyles of Draper Labs
  - The flight hardware was fabricated by Raytheon, weighed ≈70 lbs. and used only 55 W of power

- Most of the LM software was stored in Read-Only-Memory created by weaving copper wire around or through magnetic cores (called a “core-rope memory”)
  - This software provided all of the instructions for the LM to execute the Braking, Approach, Landing and Ascent Phases of the LM mission
  - Although there was a limited amount of what we think of today as RAM, the LM largely operated on preset, ROM-loaded routines that were specific to a particular landing mission – in effect, Apollo 14 could only go to the planned Apollo 14 landing site

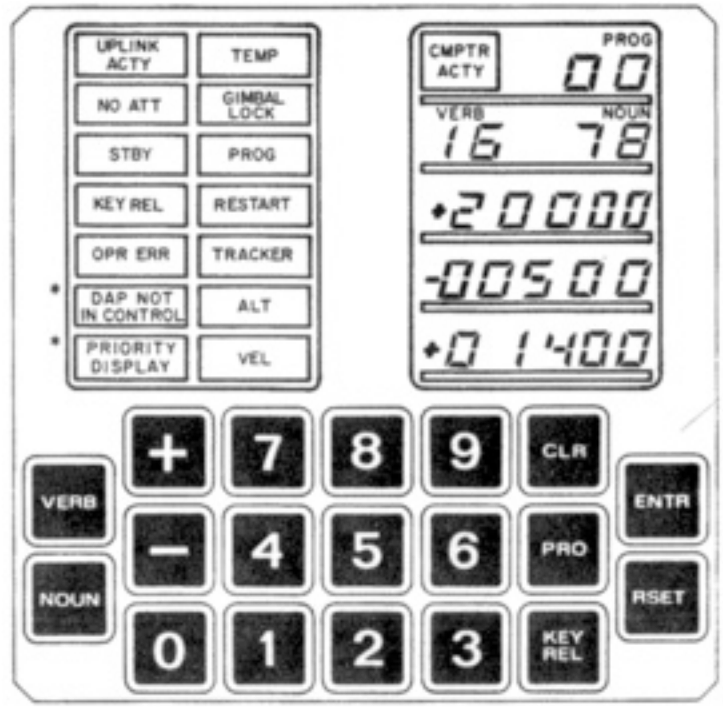
- Interface with the LGC by the crew was through the Display/Keyboard (DSKY)

Apollo Lunar Approach and Landing – LM Systems

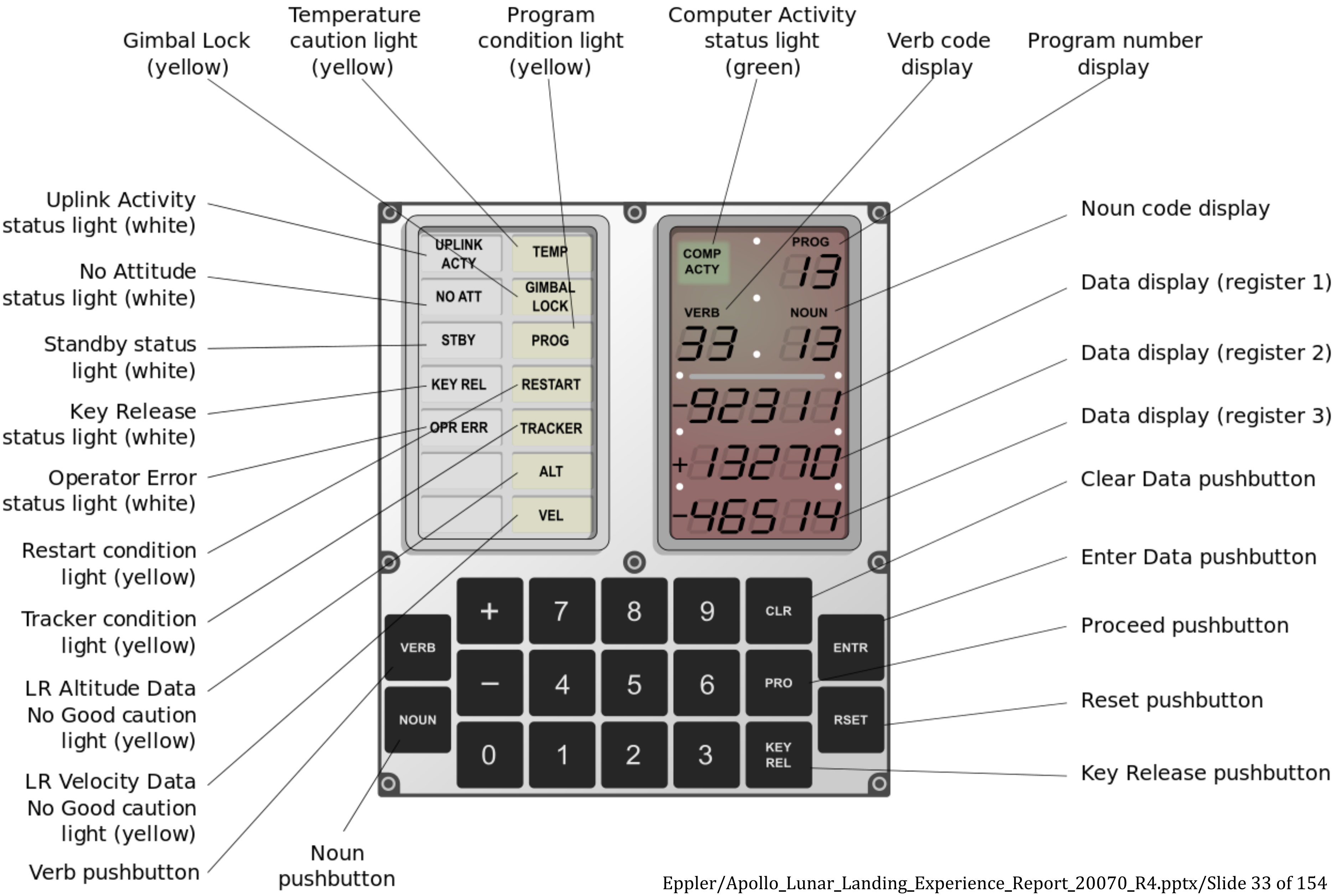
- The DSKY provided basic interface between the crew and the computer, allowing the crew to initiate programs, display critical vehicle navigational data and get information about computer issues, such as error codes

- The interface consisted of two lines that displayed the main program running at the time (there were often several programs running simultaneously, although only one was displayed in the DSKY) and relevant verb/noun combinations, three lines of data display (Register 1, 2 and 3)

- In addition to the navigation data displayed in the upper right, there was a computer status display on the upper left and an input keyboard below with a "hand-calculator-type" interface and specific action buttons for uploading and initiating programs, and entering appropriate noun-verb combinations



Apollo Lunar Approach and Landing – LM Systems



Apollo Lunar Approach and Landing – LM Systems

- LGC programs
  - The nominal and contingency actions of the LM during flight were controlled by a series of programs that executed specific actions for the LM to either land on the Moon, conduct a nominal ascent back to the CSM or abort back to the CSM
  - The specific programs that executed landing phases were the P60 programs:
    - P63 – Braking Phase
    - P64 – Approach Phase, High Gate to Low Gate
    - P65, P66 and P67 – Landing Phase, Low Gate to Touchdown
    - P68 – Landing Confirmation
  - For Apollos 9 through 12, there were separate programs for different landing methods, including:
    - P65 which was a completely automatic landing
    - P66, which put some of the key landing elements under crew control
    - P67 which was a full manual landing, specifically, disconnecting the LGC from the "action chain", with the CDR subsequently directly flying the LM, controlling DPS thrust and RCS firings using the translational (TTCA) and rotational (ACA) hand controllers
    - However, it was discovered that entry into P65 or P67 would not allow the crew to switch back to intermediate landing modes between full auto and full manual
    - After Apollo 12, different modes of crew control were compiled into P66 as separate "execution activities" that could be initiated during the Landing Phase
- One of the puzzles in doing this study was interpreting what a CDR actually meant when he said, "I took it out of AUTO and landed it manually…"

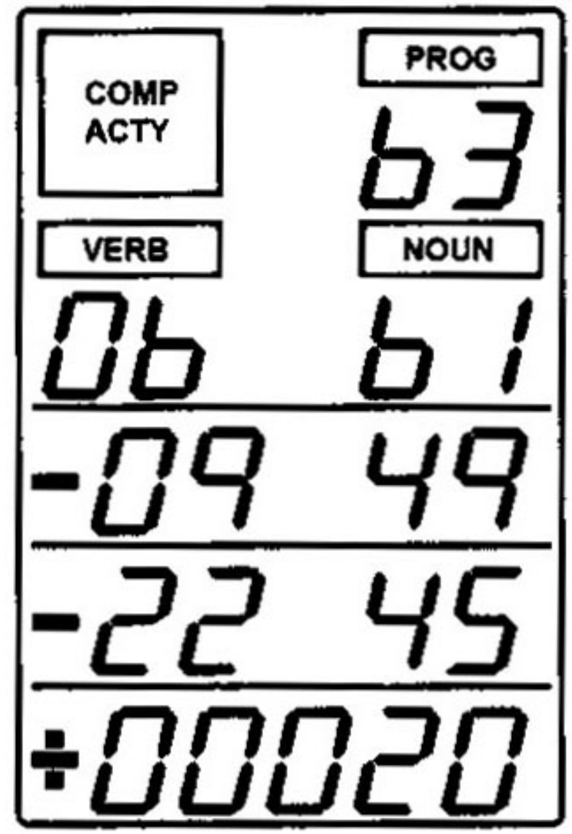
Apollo Lunar Approach and Landing – LM Systems

- LGC verbs and nouns
  - Verbs were specific actions that could tell the computer to display and/or update data or carry out a specific action, expressed as a 2-digit code, e.g., VERB 57, which permitted landing radar updates; VERB 16 was to display data; VERB 25 was to update data
  - Nouns specified the data that would be used by the computer to complete a specific action, such as Noun 95, which displayed data on a completed burn on the DKSY to compare to the pre-burn planning numbers
  - A DSKY Sequence of events could look like this (e.g., initiating Braking Phase):
    - VERB 37 ENTER (V37 means "change program")
    - 63 ENTER (means "execute Braking Phase Program 63")
    - Once the computer was ready (and there were numerous steps in P63 before this happened), it displayed a flashing VERB 99 in the Verb-Noun register – this was saying "Enable engine firing" and it was flashed at T_{ig} = – 5 seconds
    - At T_{ig} = 0, the crew would hit the PROCEED (PRO) button, telling the LGC to initiate the burn
    - On a checklist this would be shown as:

V37 ENT 63 ENT V99 N61 PRO

Apollo Lunar Approach and Landing – LM Systems

- The DSKY display on the right shows:
  - Program P63 entered
  - VERB 06, which prompts the LGC to display specific P63 data in digital form on the DSKY;
  - NOUN 61, which specifies which data to display on the lower 3 data displays (from top to bottom, Registers 1, 2 and 3), specifically
    - T_{GO} in P63, 9 mins 49 secs to completion (this would remain at -09 49 until T_{IG} reached 0 00)
    - T_{IG} for P63, Ignition in 22 mins 45 secs
    - Crossrange to the landing site in tenths of km



Simulated DSKY Data scanned from Don Eyles, Sunburst and Luminary, pg. 143.

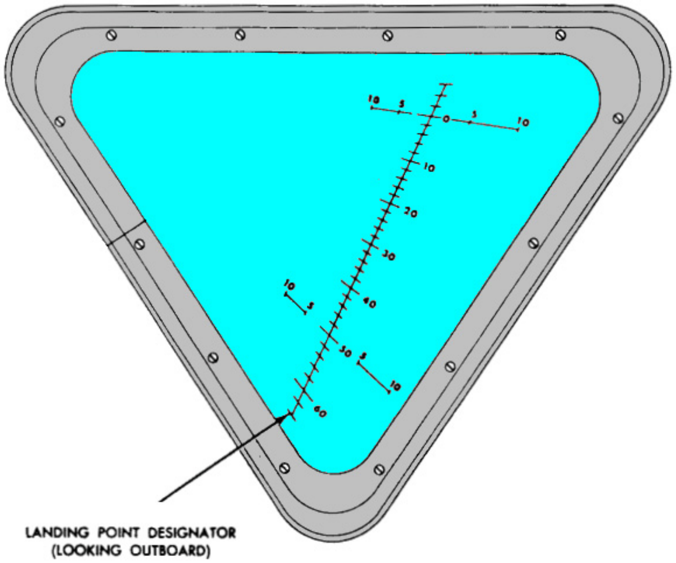
Apollo Lunar Approach and Landing – LM Systems

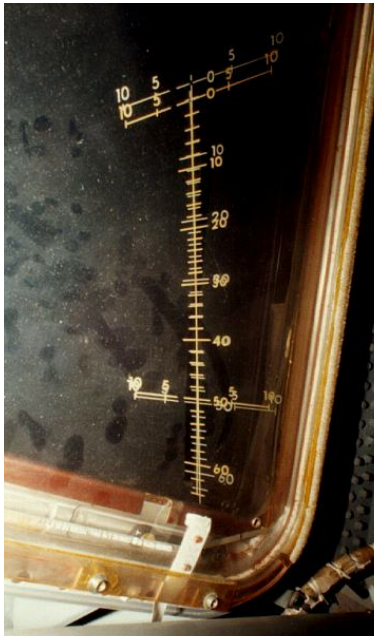
- LM Cockpit Controls
  - The LM cockpit had two primary controls that were provided for both the CDR and the LMP
    - To the left of each crewmember was a T-handle called the Thrust/Translation Controller Assembly (TTCA)
      - During on-orbit maneuvering, the TTCA was configured to allow the LM to translate using the RCS jets
      - During the lunar landing, the TTCA was configured to serve as the throttle control for DPS, with hard stops at 10% and 92.5% thrust and a soft stop at 62.5% thrust
      - In addition on the CDR side, there was a toggle switch just to the right of the TTCA, called the Rate of Descent (ROD) switch, that could incrementally control the rate of descent of the LM during the Landing Phase
    - To the right of each crewmember was a stick-type control called the Attitude Controller Assembly (ACA)
      - The ACA had two critical roles – first, control the LM attitude during flight, and second, provide direction to the LGC for landing site redesignation during landing
      - During RCS firing, the ACA worked on in two modes – a quick pulse told the LGC to fire the RCS in a single pulse, while a rotating the ACA to its hard stop disconnected the LGC inputs and fired the RCS as long as the ACA was held in position
      - During the landing, rotating the LM attitude pointed the DPS engine directly, giving it a lateral thrust vector and allowing the LM to move both forward and backward or left and right

  - Both the ACA and ROD switch could be used to provide the LGC with commands to translate the LM to an appropriate landing spot and/or modify the rate of descent based on a real-time assessment of the approach

Apollo Lunar Approach and Landing – LM Systems

- The Commander's window – Landing Point Designator (LPD)
  - The left hand window of the LM was scribed on both the primary and redundant pressure panes with a vertical and horizontal scale that defined degrees down and degrees left and right
    - With the angle data scribed on both panes, it allowed the window to act as a nomograph – when the CDR lined up a particular angle on both panes, the point he was looking at on the surface would be the spot the LM was heading toward
    - During the Approach Phase, the LGC would provide an numerical value, called the LPD angle, based on the LM instantaneous state vector, pitch attitude and subsequent propagated trajectory, which the CDR lined up on to see the surface location that the LM was headed for
    - In this way, the window would act like Precision Approach Path Indicator (PAPI) lights on a runway
  - The LMP was responsible for calling those "look down numbers" out to the CDR so he could decide on the suitability of the targeted landing spot, and make real-time decisions on whether to re-targeted the LM to a more suitable landing spot





Apollo Lunar Approach and Landing – LM Systems

- The Crew
  - OK, the guys on board are obviously not hardware, but the Commander (CDR) and Lunar Module Pilot (LMP) were a critical part of the LM system and performed roles that, in concert with the hardware, effected 6 successful landings on the Moon
  - The Commander
    - The CDR was Pilot-in-Command in the purest 14 CFR Part 91.3 sense: the primary decision maker for flight safety, for selection of the specific landing spot and for decisions related to aborting or continuing a particular lunar descent
    - There were obvious flight rules that governed specific aborts based on hardware issues or failures, and clearly the flight controllers, represented by the Flight Director, had significant input to flight decision-making, *but*…
      - During the Approach and Landing Phases (<4 mins *total* duration), the data the ground was receiving was 1¼ seconds late, and subsequent ground calls would take another 1¼ seconds to get back to the crew, making real-time decision making by the CDR a critical part of landing
    - Accordingly, throughout the final approach and landing phase, a successful landing or abort was entirely the responsibility of the CDR

Apollo Lunar Approach and Landing – LM Systems

- The Crew (continued…)
  - The Lunar Module Pilot
    - The LMP was a true co-pilot, and acted in the same role that co-pilots act on airline and military flights:
      - Provide data to the pilot-in-command on the projected landing spot, including LPD angles, rates of descent, lateral velocity and fuel remaining
      - Monitor spacecraft systems and generally provide the data that the CDR would need for landing decisions so he could keep his eyes outside the cockpit on the landing site
    - During the Powered Descent phase, the LMP was *generally* responsible for inputs to the LGC through the Display/Keyboard (DSKY)
      - Some CDRs preferred to be the guy that did the inputs to the DSKY
      - In this case, the LMP was the person that did acted as safety backup, confirming the inputs before executing a particular guidance program
    - In any event, the LMP was usually the crew expert on the LGC and the Landing Radar, and understood how to make the systems work together

- In summary, the LM was a vehicle that required two pilots, and while in theory it could be landed automatically, every approach and touch down had significant crew input during the Approach and Landing Phases
  - In particular, on every mission (not just Apollo 11), the initial landing point targeted by the automatic system was, in the CDRs assessment, unsatisfactory
  - While the CDR was never flying the LM in a "direct mode" (more on that later), every CDR needed to select a better, alternate landing spot and drive the P66 activity through to landing and engine stop

How We Did It –
Aborts and Abort Modes

Aborts and Abort Modes – How, When, Why

- Any discussion of landing aborts and abort modes should be informed by the crew's view of aborts:

  - Neil Armstrong: *"Well, I think -- in simulations we have a large number of failures and we are usually spring-loaded to the abort position and in this case, in the real flight, we are spring-loaded to the land position. We were certainly going to continue with the descent as long as we could safely do so…our procedure throughout the preparation phase was to always try to keep going as long as we could ...* (Apollo 11 Post-flight Press Conference at MSC, 12 August 1969)"

  - Gene Cernan : *"We used to play around in the simulator to see if the AGS gave us enough information to land; and, quite honestly, if we were close I think we could have landed. There was a mission rule, as I remember, that we wouldn't land if we had a primary guidance failure. But one thing that people never paid much attention to is that, for most of the flight - and this is one very visible point - the ground has no control over what you're doing…you're in command, you're flying the machine, and you're making the decisions. So who is to know what decision would have been made if you were down around three or four hundred feet or six hundred feet or a thousand feet and you had a question about your primary navigation system but your abort navigation system looked good…we didn't want to go that far and not land because of a computer problem."* (ALSJ, Apollo 17, Debrief comments at MET 112:50:39)

- In short, while landing aborts are often defined by hard rules, the actual in flight application of those rules would have been informed by the crew's interpretation of what was reasonable at a particular moment

Aborts– General Conditions, Responsibilities and Modes

- Abort Conditions/Responsibilities – General
  - MSC Houston (MCC-H) was responsible for detecting “slow, insidious drift malfunctions” that might contribute to aborts
    - This required as much high rate data between the LM and the ground as possible, as downlinked telemetry gave the flight controllers the information to detect this malfunctions
  - The crew was responsible for detecting errors that require immediate action, largely because communications cycle time for an immediate abort would be as long as 20 seconds
  - The abort modes discussed below cover general conditions – there are pages of detailed abort conditions and actions that are summarized in the backup slides

- Abort modes
  - The LM had two abort modes Abort and Abort/Stage, based on the conditions causing the abort and the time during the landing when abort was initiated
  - An abort that used the ascent and descent stages – i.e., aborts initiated when the failure did not involve significant degradation of the DPS – was referred to as an Abort
    - In this case, the DPS was used to start the LM stack (***<u>both</u>*** Ascent and Descent stages) back uphill toward into an orbit where the LM could rendezvous with the CSM
    - The DPS continued firing until fuel was exhausted, at which point the Descent Stage was jettisoned and the rendezvous was continued using the Ascent Propulsion System
    - This abort required pitching the LM to reorient the thrust vector of the DPS such that the climbout began as soon as possible after the abort condition was detected

Aborts– General Conditions, Responsibilities and Modes

- Abort modes (cont.)
  - An “Abort/Stage” abort was initiated when a failure of the DPS occurred at any time during the landing sequence
  - This involved jettisoning the Descent Stage and initiating an immediate burn on the Ascent Propulsion System
    - Abort/Stage meant that explosive devices severed the electrical and data connections to the Descent Stage and conducted an immediate “fire in the hole” burn with the Ascent Propulsion System
  - It was assumed that the “decision cycle” to initiate an Abort/Stage was ≥4 sec

- Abort/Stage abort boundaries
  - During the Approach and Landing Phases of the flight, there were critical abort boundary conditions that drove whether the LM could, in fact, successfully do an Abort/Stage
    - These boundary curves were similar to the altitude-airspeed curve that defines whether a helicopter can successfully auto-rotate in the event of a complete engine failure
  - A Bellcomm memo (ref 2.) defined the following formula:

$$\text{Minimum safe altitude} = |80\text{ ft} + 10*\text{H-dot}|$$

  - What this meant is that if the [80+10*H-dot] value was less than the altitude of the LM at that time, there was insufficient time and height above the lunar surface to execute an Abort/Stage
  - While the CDRs did a good job of staying above that altitude boundary, you can do the math and see that below ≈100 ft with an H-dot >2 ft s^{-1}, the LM was committed to a landing

Specific Abort Conditions

- Abort or Abort/Stage decision would be made when malfunctions precluded a safe descent and landing, or inability to abort later in the landing sequence
  - Abort (not Abort/Stage) procedures were designed to place the LM in an orbit with a periapsis >30,000' and in a position to rendezvous with the CSM on the Ascent Propulsion System

- Overall abort decision points
  - General
    - Loss of S-band high rate data or voice communications
    - CSM malfunctions that may affect rescue capability
  - Propulsion systems
    - Zero or low DPS thrust
      - Failure of the DPS to start automatically after P63 PRO and after an attempted manual start by the CDR
      - DPS entry into a degraded condition, abort to be initiated *after* attempted CDR manual start using the Descent Engine Start switch
    - Failure of the DPS to throttle
    - Impending DPS propellant depletion
    - Loss of APS redundant start capability
    - Uncontrollable DPS gimbal failure

Specific Abort Conditions (cont.)

- Overall abort decision points (cont.)
  - Guidance and Navigation
    - PGNCS malfunction
    - AGS malfunction prior to High Gate (P63-P64 transition at Pitchover)
    - Lack of Landing Radar (LR) data
    - Incompatible difference between PGNCS and LR data
  - Trajectory constraints
    - Violation of specific abort limits seen on MCC-H displays, data not available to the LM crew; in this case, the Flight Director would call the abort
  - Landing Site Condition
    - Unsatisfactory for safe landing
    - Redesignation unreasonable given LM trajectory and fuel state

- If you look at the history of various landings, clearly some of these abort rules were subject to some interpretation
  - For instance, the Apollo 11 landing had very ratty comms throughout the Braking Phase, requiring several yaw maneuvers to put the LM high gain antenna in a more favorable position
    - If the abort rule on communications had been strictly enforced, Apollo 11 might have had to abort very early in the Powered Descent

How We Did It –
How Vehicle Roles Changed as Apollo Evolved

Lunar Descent and Landing – Changing Vehicle Roles for Descent Orbit Insertion

- Remember back to our four phases of a landing, Phase 1 is Descent Orbit Insertion, which put the LM in an orbit from which to start down to the lunar surface

- Descent Orbit Insertion (DOI) Burn
  - On Apollos 11 and 12, the DPS initiated the burn after separation from the CSM on the lunar far side, out of contact with the ground
    - This burn was done after P52 guidance system alignment by the LM, and getting a state vector uplink to the LM prior to Loss of Signal (LOS) as the LM went behind the Moon
    - This was clearly a very busy evolution
  - The DOI burn was ≈30 seconds long, with a ΔV of <100 ft s^{-1} performed by the DPS
    - The use of the DPS meant that ≈30 seconds of fuel was not available for the actual descent and landing
      - 30 seconds doesn't sound like much, but *literally* every second of DPS fuel counted
      - A good example of the importance of seconds of burn time is the removal of the ≈200kg Apollo Lunar Scientific Experiments Package from the Apollo 11 manifest, in order to give the LM *three additional seconds* of fuel burn

Lunar Descent and Landing – Changing Vehicle Roles for Descent Orbit Insertion (cont.)

- After Apollo 12, it was decided that on future missions, the DOI burn would be handled by the CSM, leaving the total DPS ΔV budget available for descent and landing
  - The SPS DOI burn was ≈23 seconds long, with a ΔV of ≈200 ft s^{-1}
    - This shift of DOI responsibility was done to increase hover time for the LM over the increasingly challenging landing areas, and to increase the landed downmass
    - By the time detailed planning for Apollo 13 was undertaken, Apollo Program management had developed sufficient confidence in the Service Propulsion System to transfer the DOI burn responsibility to the CSM

- However, there were a number of key post-DOI burn events that had to occur *before* the LM could initiate PDI
  - The CSM-LM stack had to be in a safe orbit prior to undocking
    - An SPS overburn during the DOI burn of only 1 second would leave the stack in an orbit that would impact the Moon in a successive orbit
      - A “bail out burn” was scheduled ≈35 minutes after DOI to get the stack back into a safe orbit if there was a significant overburn
  - The LM had to safely separate from the CSM and both vehicles had to have a clean systems check
  - The CSM had to successfully initiate a burn back up to the 60 nm circular orbit
    - This meant that the SPS had to check out prior to the burn
    - If the SPS did not fire properly, the landing would have to be aborted and the DPS would take the re-docked stack back up to the 60 nm orbit
      - On Apollo 16, the LM landing was delayed because of an issue with SPS gimballing that took several orbits beyond the nominal CSM circularization burn to be cleared and allow PDI

How We Did It –
Landing Site Constraints

Lunar Descent and Landing
Constraints for Landing Site Selection

- During the later Apollo missions (specifically Apollo 15, 16 and 17), a great deal of appropriate emphasis was made on selecting sites that the science community felt would answer lunar science questions

- However, for all landing sites under consideration, there were key operational constraints that had to be satisfied, regardless of how important the science was
  - These constraints ultimately "rattled back" onto launch window dates, launch window durations, the launch inclination the Saturn V stack and the duration of various mission phases leading up to landing (for a great discussion, see https://history.nasa.gov/afj/launchwindow/lw1.html)
  - In particular, this meant that Apollo launch windows were roughly a month apart, and it's why Apollo 8 had to be orbiting the Moon during Christmas, 1968

Lunar Descent and Landing
Constraints for Landing Site Selection

- Landing Site Lighting
  - In order to safely land, the crew had to be able to assess the “LM-scale” surface roughness of the landing spot prior to touching down, which required lighting that would enhance surface topography
  - It’s really important to emphasize that during Apollo, our understanding of “footpad-scale” topography was very poor for each site except the Apollo 17 site
  - This meant that the landing site had to be lit from behind the LM during it’s approach, with a sun angle between 5° and 14° above the horizon, so that at pitchover the crew could see the topographic features of the landing site
  - This meant that the final approach ground track azimuth had to be oriented so the Sun was behind the LM at pitchover

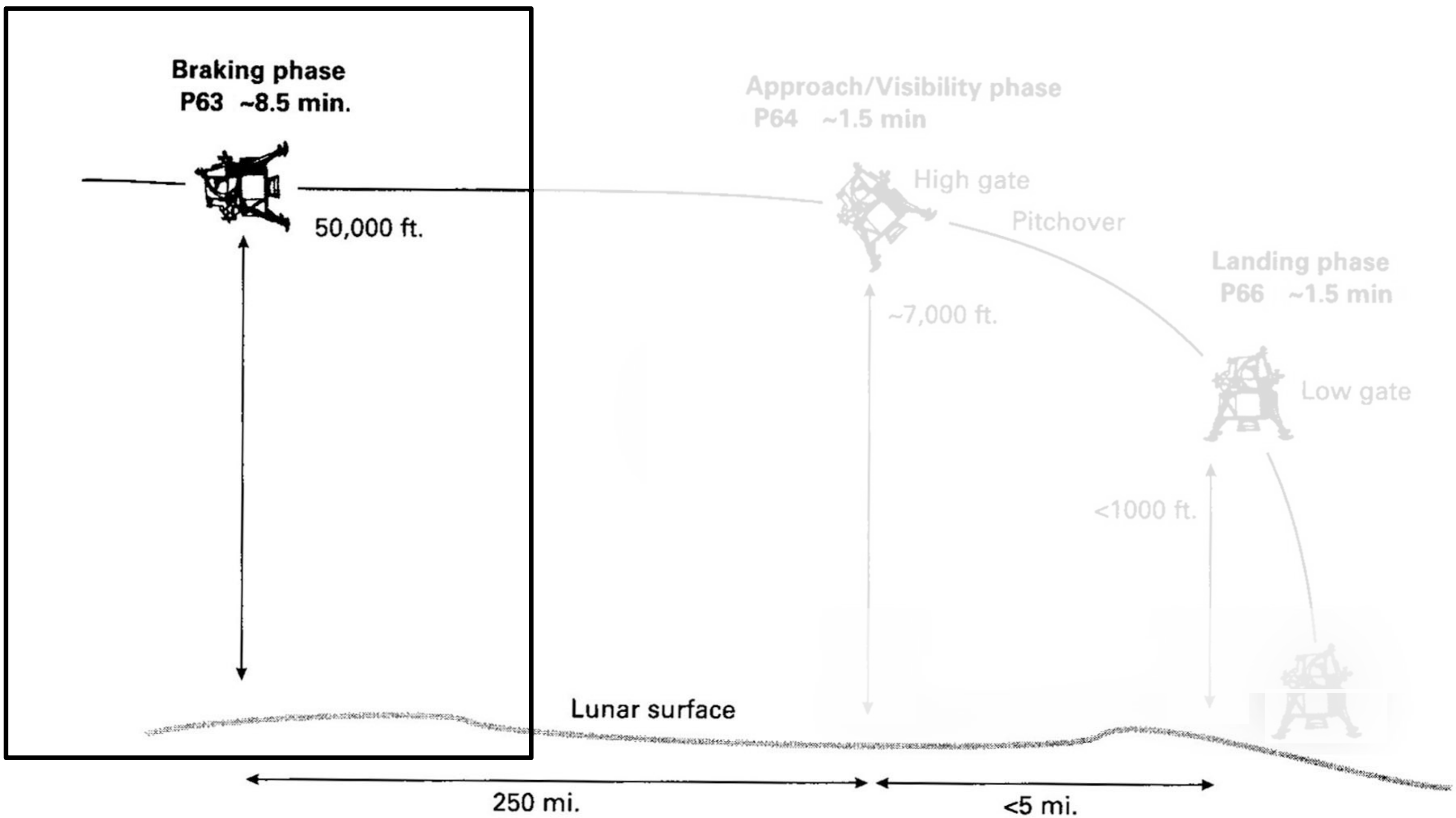
- State Vector Update and Trajectory Confirmation
  - The other critical operational constraint was that the LM state vector had to updated prior to PDI based on uplink data from the ground and position checks in orbit
  - The former, in particular, could not be accomplished until the ground reacquired the LM when it emerged from the lunar far side
  - Once in contact, it was necessary for the ground determine and uplink the LM state vector prior to PDI – this took time, and consequently eliminated landing sites that were on the far eastern limb of the Moon

- Note that we will almost certainly have the same constraints for any future lunar landing, regardless of the targeted landing site

How We Did It –
The Nuts and Bolts of Flying an Actual Landing

Lunar Descent and Landing – How We Actually Did It

- The Braking Phase



Lunar Descent and Landing – Braking Phase

- The Braking Phase was initiated by the Powered Descent Insertion (PDI) burn, performed by the DPS ≈250 n.m. uprange of the landing site
  - PDI was controlled by the LGC running the P63 program, which was called up by the crew ≈10-15 minutes before DPS ignition
  - P63 went through a pre-burn targeting routine which set the LM up for the burn
  - This would be a V37 ENTER 63 ENTER, followed by a flashing VERB 06 NOUN 61 confirming the key data for the braking phase: T_{GO}, T_{IG} and cross range

- PDI was preceded by a number of key navigation checks and updates that were done by either the ground over the Manned Space Flight Network (MSFN) or the crew in the LM using the optical sighting system and doing a Platform Alignment using the LGC Program P52

  - The first check was transferring the CSM platform alignment to the LM about an hour before undocking, which provided a coarse platform alignment, and a subsequent P52 platform optical fine alignment by the LM crew using the LM optical system after undocking
    - At this point, the LMP would update the AGS as well, so both guidance systems had the same state vector data prior to initiating the burn to the surface

  - The second check was an LM state vector update, which was uploaded into the LGC by the ground through the MSFN after LM AOS, with crew authorization, at about PDI -30 mins
    - This ensured that the LGC had the latest understanding of where it was in space, and how fast it was going in which direction
    - The LGC then updated the LM state vector every 2 seconds, based on input from the PNGCS, which used the inertial platform to sense orientation and acceleration during Powered Descent

Lunar Descent and Landing – Braking Phase

- Pre-PDI Checks (cont.)
  - The third check was done by the crew using the LM optical tracking system to check at what time they passed a number of geographic points on the lunar surface
    - These points were selected prior to the mission, and the crew had a table of nominal overflight times
    - If they overflew these points early or late it would tell them that they were targeting long or short on the landing site
    - For instance, on Apollo 11, at MET 102:36:30 Armstrong reported that they had overflown a ground target ≈3 seconds early, indicating that they would be ≈3 mi downrange of the intended landing point

  - The fourth check prior to engine ignition involved the LGC running a subroutine called "Average g"
    - Average g was a complicated integration of a platform data and assessments of the value of the lunar gravity field that was designed to correct the initial state vector for the effects of lunar gravity
      - When the LGC began Average g, the DSKY would go momentarily blank and then reset
    - Given the known "lumpiness" of the lunar gravity field (blame geology and isostasic disequilibrium), Average g was critical to correct the state vector prior to the start of powered descent

Lunar Descent and Landing – Braking Phase

- PDI was initiated by preceded by a brief ullage burn (≈7.5 seconds) done with the RCS to bring the DPS fuel and oxidizer to the bottom of the tanks where it could flow into the engine once the burn was initiated
  - Once the ullage burn initiated, at PDI T_{IG}=-5 sec, the LGC would flash VERB 99 NOUN 62 on the DSKY, essentially saying, "I'm ready to go with P63 when you are (V99), and here's the data you'll need to monitor (N62))"
  - The crew would hit PRO on the DSKY, which would tell the computer to proceed with P63 and start PDI

- At PDI, the DPS went through two actions
  - An ≈26 second burn at 10% thrust, which allowed the DPS gimbals to align the engine thrust vector through the LM center-of-gravity (C_g)
  - At T_{ig} ≈+26 seconds, the DPS throttled up to >92.5% thrust, reducing the LM forward velocity and starting down to the lunar surface

Lunar Descent and Landing – Braking Phase

- At this point (except for Apollo 11), the LM is pointed face up and engine-bell-forward, making it impossible for the crew to pick up subsequent check points
  - During Apollo 11, the LM was face down for post-PDI geographic position checks
  - At around 3 minutes into Powered Descent, Eagle was yawed to face up, engine bell forward
  - After that yaw maneuver, Armstrong and Aldrin were in the same attitude as subsequent landings - flying blind, face up – and they had to rely on the LGC and ground assessments of their trajectory to know if the landing evolution was proceeding in a nominal fashion
  - The LM would start Powered Descent in an attitude that was pitched up ≈100°, and as the Braking Phase continued, the pitch would gradually decrease to <60° just prior to transition to the Approach Phase
    - During Powered Descent, the LMP often gives the CDR cues on "the Ball number", which is a reference to the pitch angle he can see on the Flight Director Attitude Indicator (FDAI) or simply, "the Ball"

- Throughout Powered Descent, the LGC is flying the LM by automatically commanding two systems: the DPS and the RCS
  - The RCS did a variety of short firings commanded by the LGC to compensate external disturbances like fuel sloshing in the prop tanks
  - The LM simulators at KSC and JSC did not simulate this and on Apollos 11 and 12, there are crew comments about how the "RCS is banging away" during P63
  - This is a *very* dynamic phase – the LM weight and C_g is changing, the trajectory is varying constantly, and the LGC is furiously calculating state vectors, altitudes and range to the landing site every 2 seconds

Lunar Descent and Landing – Braking Phase

- The key crew task here is to monitor the progress of the burn against the "theoretical" perfect powered descent (displayed on a "cheat sheet" velcroed to the instrument panel) using the 1) H, H-dot and Range-to-Landing data shown on the DSKY, 2) fuel and oxidizer quantities and 3) a PGNCS to AGS comparison, and to ensure that key data sources like the Landing Radar provide data to the LGC at the appropriate times

- The ground would also monitor the LM position with MSFN-acquired tracking data and project a landing point, and could determine potential over- or under-shoots of the landing site using a program called DLAND that was implemented after Apollo 11
  - As appropriate, the crew could update the LGC using a VERB 21 NOUN 69 on the DSKY to enter an uprange or downrange correction
  - However, an incorrectly entered NOUN 69 entry could cause significant problems, so the the N69 ENTER was only done when the crew and the ground agreed on the parameters to be entered and confirmed that they were typed correctly into the DSKY prior to proceeding

- In addition, the LMP would periodically manually update the AGS (which did not get Landing Radar data) on a separate keyboard (the DEDA) with the altitude readout from the DSKY
  - For example, the LMP could key in 18,000' into the DEDA and when the DSKY showed an H value of 18000, he would hit ENTER on the AGS keyboard, updating the AGS data

Lunar Descent and Landing – Braking Phase

- At about 3 minutes into Powered Descent, the next critical event was the Landing Radar getting good returns from the the surface ("radar lock") at ≈40,000 ft
  - Based on both a crew and ground check of the quality of the radar data, the crew would tell the LGC to accept that data and use it in the recurring state vector updates
    - The radar data "quality" was checked using a LGC function called "Delta-H" which compared the radar H with the LGC calculated H
      - For the first part of the Braking Phase, H and H-dot were based on state vector data and often had pretty big error bars
      - Very often during the first part of powered descent, you can often hear the LMP calling "H and H-dot are a little high…"
      - Being a little high was OK – for "Kentucky windage", the approaches were often started high and H and H-dot converged as they got closer to the landing site
      - A good Delta-H calculation was essential to confirm radar data quality
  - Good radar lock was a big deal – without Landing Radar data, the crew would have to abort, as pure state vector data alone was not considered sufficiently precise to be the sole navigational source for landing
    - Gene Cernan, on Apollo 17, obliquely referred to the nominal time for acquisition of good radar data as, "The Day of Reckoning"…

- Also at ≈3 minutes into the burn, the crew do the "ED Batts Check", to confirm the batteries that fired the explosive devices in the event of an "Abort/Stage" abort were working

Lunar Descent and Landing – Braking Phase

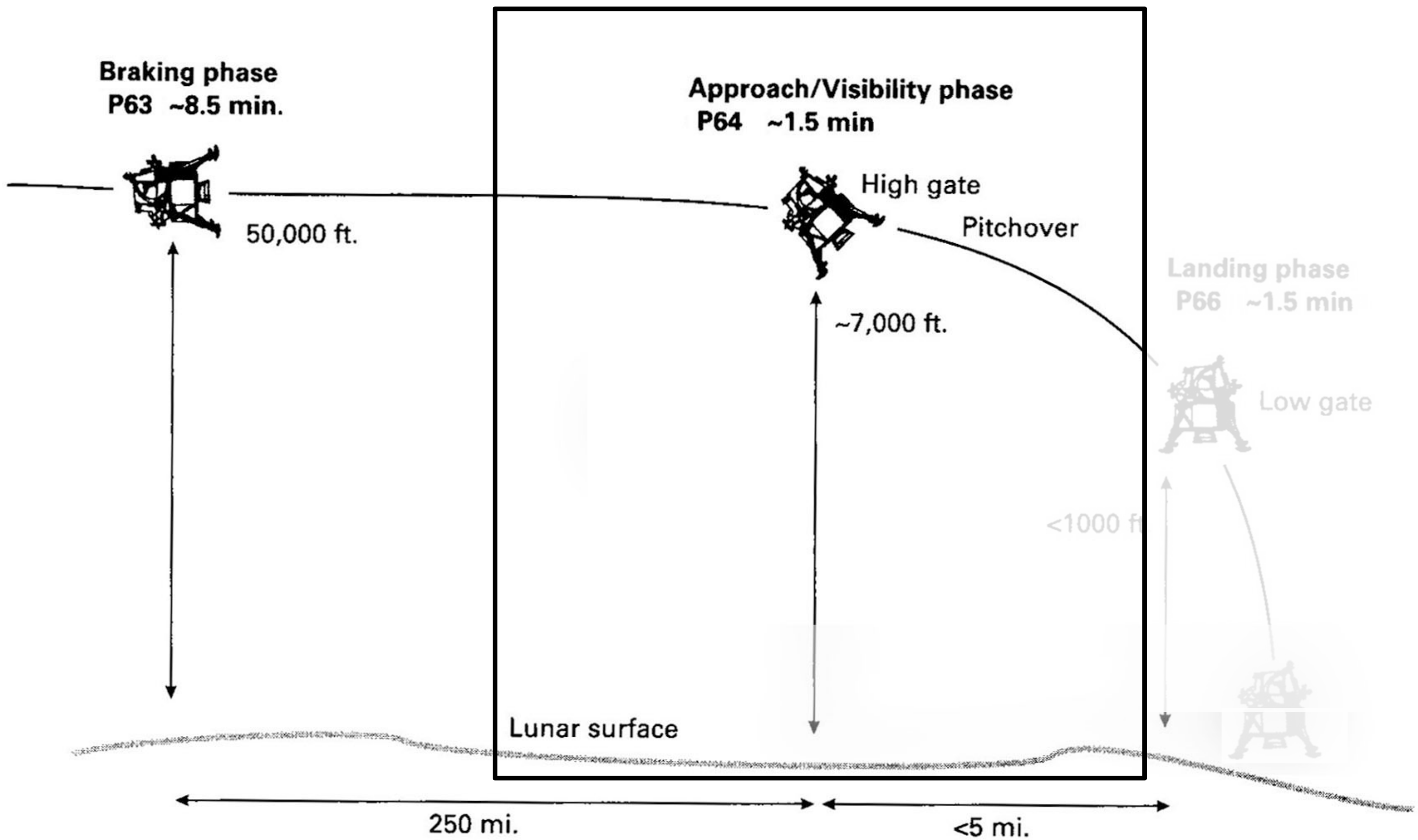
- In addition, the ground would monitor the fuel gauges and choose the most conservative for the crew to monitor
  - There were two independent systems for measuring fuel and oxidizer remaining, so early on in powered descent, the ground would make a decision on which set of gauges to watch
    - A switch on LM Panel 1 allowed the crew to select which gauge they would monitor during approach
  - This was done to ensure that the crew was conservative on fuel during the approach and landing phases
  - A typical call would be for the crew to "Monitor Descent Fuel 2"

- Lastly, the CDR would briefly change the PGNCS Mode Control switch from AUTO to ATT HOLD, which would allow him to check the handling of the LM before going into the final landing phase

- At around 7 mins, 30 seconds, the DPS would go through "Throttle Recovery" - throttle down to ≈57%, from the full power setting initially used during Powered Descent, to avoid the power settings where significant DPS throttle assembly erosion occurred
  - The "throttle down" call was a critical one, as it was impossible to land the LM at full power, or if the throttle went too far down and wouldn't recover
    - This call took place about 2 minutes before the transition from the Braking Phase to the Approach Phase (P63-P64 transition)

Lunar Descent and Landing – How We Actually Did It

- The Approach Phase



Lunar Descent and Landing – Approach Phase

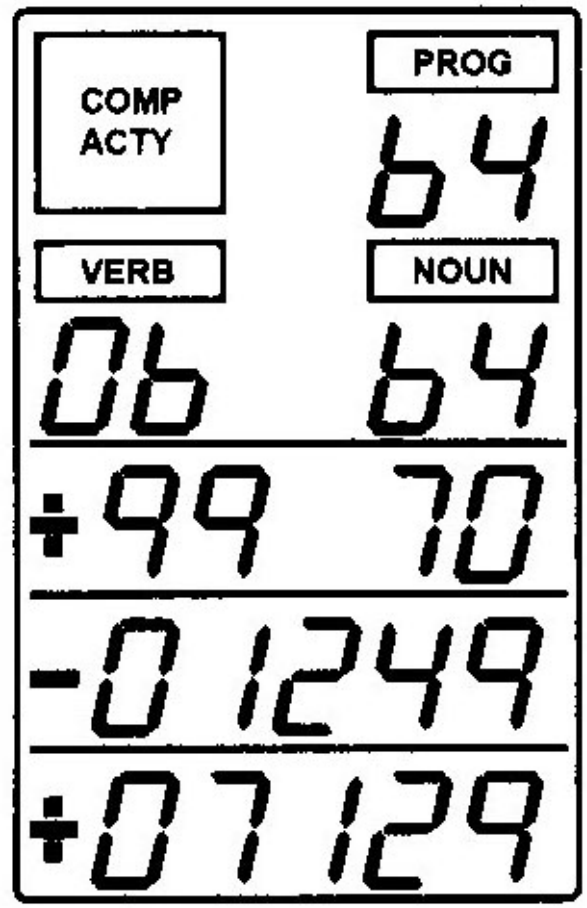
- As the crew flew the Braking Phase, they were gradually losing altitude and velocity, headed toward "High Gate" and Approach Phase transition
  - Throughout the last ≈8 minutes of Powered Descent, the crew was face up allowing the Landing Radar to see the lunar surface and provide the appropriate H, H-dot and range to the landing site data to the LGC

- Approach Phase Initiation
  - The Approach Phase started at about 7,000' AGL when LGC program P64 initiated the pitchover maneuver
  - This pitched the LM around its Y-axis from the feet-forward, face-to-the-sky attitude to one where the crew could now see the landing site for the first time
  - Pitchover was a *BIG DEAL!* It meant you could tell how accurately the LGC had navigated you to the landing site, and if you were going to be able to land
  - Note this dialogue from Apollo 12 at P63-P64 transition:

110:29:17 CAPCOM Carr:	*Roger. Copy P64.*
110:29:18 Bean:	*Okay, there's 6000 update.*
110:29:20 Conrad:	*(Very excited) Hey, there it is! There it is! Son-of-a-Gun! Right down the middle of the road!!!*
110:29:25 Bean:	*Outstanding! 42 degrees, Pete.*
110:29:27 Conrad:	*Hey, it's targeted right...*
110:29:28 Conrad:	*...for the center of the crater!*
110:29:29 Bean:	*(Garbled) look out there.*
110:29:30 Conrad:	*I can't believe it!*
110:29:32 Bean:	*Amazing!! Fantastic!*

Lunar Descent and Landing – Approach Phase

- Approach Phase Initiation (cont.)
  - Approach Phase initiation was controlled by an automatic switchover keyed to T_{GO} in P63 – that is, when the T_{GO} value in P63 reached zero, the LGC would immediately shift to executing P64
  - Once the LGC was in P64, it would show a DSKY display similar to the one shown on the right (scan from Don Eyles, Sunburst and Luminary)
    - In the upper right, “64” indicates that the LGC is in P64
    - VERB 06 and NOUN 64 indicate, respectively, the displays are in decimal data in the lower three data displays, and that they are displaying:
    - In Register 1: Left, the time available to redesignate the landing point, and right, the LPD angle that the CDR needs to look to see the targeted site
    - In Register 2: The computed H-dot in ft s^{-1} (there is an “assumed” decimal point between the two digits to the right; “1249” is actually 124.9 ft s^{-1})
    - In Register 3: H from Landing Radar data
- When the LGC went into P64, the Verb/Noun line flashed, meaning the LGC was asking, “Is this OK”?
  - Either the LMP or CDR would then hit PRO to accept the data



Apollo 11 DSKY at the start of P64, captured while the LM is in the process of pitching over.
Time to completion of P64: 99 s
LPD angle: 70°
H-dot: 124.9 ft s-1
H: 7,129 ft

Lunar Descent and Landing – Approach Phase

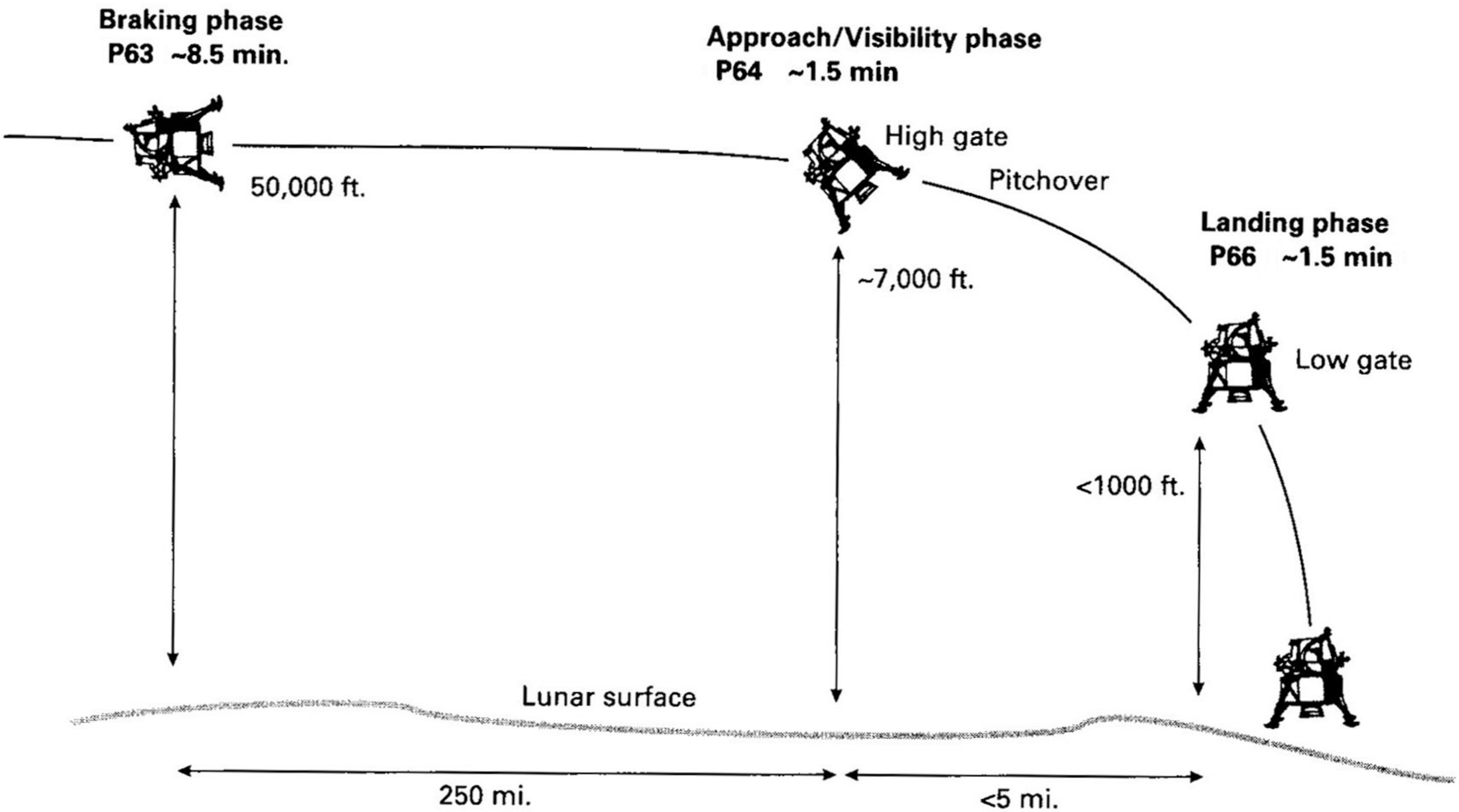
- During the landing approach, the CDRs was able to redesignate the landing spot using the ACA
  - One pulse forward or back moved the landing spot 0.5°
  - One pulse left or right would move the landing spot 2°

- Dave Scott, for instance, found that, *"We were south, and I redesignated immediately four clicks to the right (north) and then shortly thereafter…I redesignated two more to the right and three uprange.* (Dave Scott, quoted from ALSJ, crew debrief comments after MET 104:40:28)"
  - Dave Scott would ultimately make 18 redesignations, the most of any Apollo landing (quoted in Mindell, Digital Apollo, pg. 254, para. 1)

- The teamwork between the CDR, the LMP and the LM during the Approach Phase was ***the*** key to flying the LM to the landing spot
  - Unlike the Braking Phase, in P64 the crew was directly interacting with the LM through the LGC to decide where they would land
  - The LGC was still doing the nuts-and-bolts of controlling the vehicle – changing thrust, changing LM attitude – but the CDR was deciding if the spot the LGC was taking them to was good, and telling the LM where to go if it was not
  - The data that allowed the CDR to make that decision was coming out of the LGC in the form of LPD angles, H and H-dot values, read out by the LMP so the CDR could keep his head out of the cockpit to control the landing spot
  - The LMP had a cue card for a "theoretical perfect approach" that showed fuel burn rates, H and H-dot at 30 second intervals, enabling him to keep the CDR apprised on how close they are to a "perfect" approach and how close they are to fuel limits and prohibitively large H-dots

Lunar Descent and Landing – How We Actually Did It

- The Landing Phase



Lunar Descent and Landing – Landing Phase

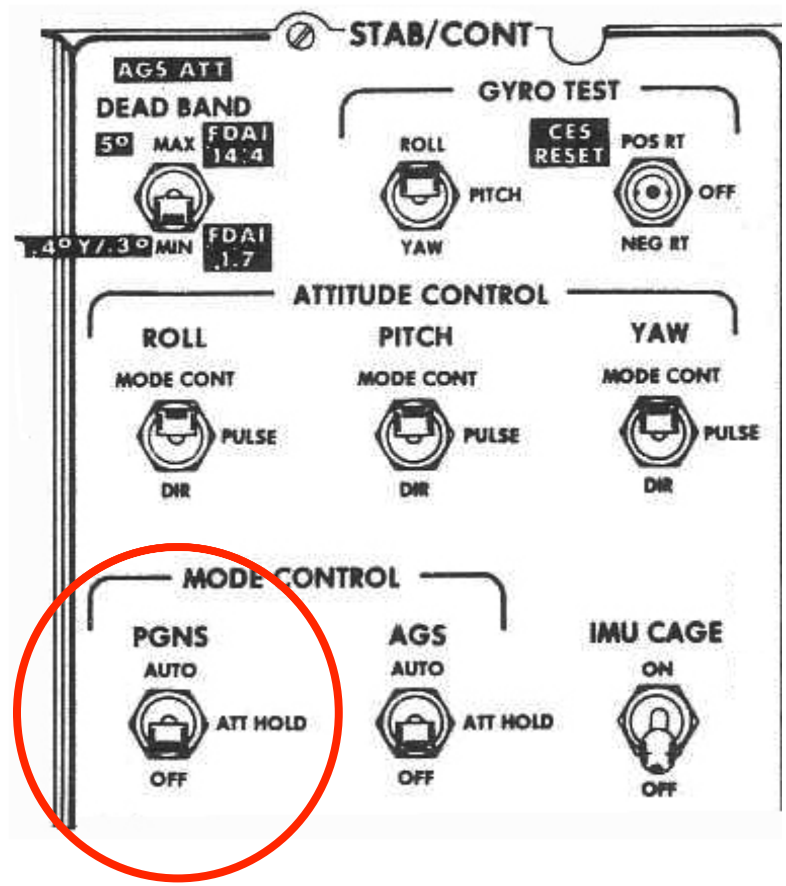
- Entry into the Landing Phase is (obviously) critical, and it's probably the least "scripted" of any of the landing phases
  - First, during Apollo, our actual knowledge of the meter-scale topography of the landing site prior to pitchover was often very poor
    - On Apollo 16, in particular, the best images we had of the landing site prior to landing didn't allow us to see anything smaller than about a 20 meter object
    - This would be equivalent to being on an actual ILS 35L approach to Ellington and when you break out, you could find that Building 45 is sitting on the approach end of 35L
  - Consequently, the transition from the Approach Phase to Landing Phase (P64-P66 transition) was dependent on the CDR designating to an acceptable landing site in P64, and getting low enough to begin to actively manage LM attitude, approach path and descent rate

- There were three options in P66
  - Full Auto – essentially stand-back and let the LM land itself, with the Landing Radar and the LGC making all the decisions about descent rates and vehicle attitudes (originally P65)
  - Attitude Hold – in this case, the LGC keeps the roll, pitch and yaw attitude of the vehicle steady and the CDR manages the descent rate, although he can command a change in attitude with the ACA (originally the only option in P66)
  - Full Manual landing – in this case, the LGC is completely out of the loop and the CDR is flying the vehicle directly, using the TTCA to control DPS thrust and the ACA to control vehicle attitude (originally P67)

Lunar Descent and Landing – Landing Phase

- Entry into P66 was accomplished by the CDR moving the PGNCS switch on the MODE CONTROL SWITCH from AUTO to ATT HOLD
  - The Mode Control Switch was on the LM STAB/CONT Panel just above the DSKY

- Once ATT HOLD was selected, the CDR would engage the ROD switch just inboard if the TTCA
  - The ROD Switch controlled the thrust in 1 ft s^{-1} increments – one "up" pulse of the switch reduced the rate of descent by 1 ft s^{-1} ; one "down" pulse increased the rate of descent by 1 ft s^{-1}
  - By pulsing the ROD switch with the ATT HOLD engaged, the LGC automatically rolls over into P66, and the landing proceeds



Lunar Descent and Landing – Landing Phase

- At this point, the CDR is flying the LM through the LGC, directing the vehicle to the chosen landing point by managing the vertical velocity with the ROD switch while LGC sends appropriate commands to the RCS to hold a chosen attitude
    - A short pulse on the ACA could pitch or roll the LM, which would change in the DPS thrust vector and cause the LM to move laterally
        - When you see the films of Eagle flying downrange above the lunar surface, this is how Armstrong is executing the approach
    - In effect, at this point, the CDRs job is to manage the LMs horizontal position using ACA inputs to the LGC, and manage the descent rate using the ROD switch until touchdown
        - Nominally, the plan was to null out any horizontal velocity (0° roll/0° pitch) and use the ROD switch to set the LM down
    - During P66, the LMP is acting as the flight engineer, feeding information on H, H-dot, lateral velocities and fuel state using the DSKY and other onboard instruments to ensure the CDR has the data he has to manage the landing
    - When you listen to the transcripts of Apollo landings, about 90% of the time, you're listening to the LMP updating the CDR with the pertinent approach data

Lunar Descent and Landing – Landing Phase

- This activity continued until one of the ≈6’ long landing probes made contact with the lunar surface and was torqued out of position, which sent a signal to illuminate the “Lunar Contact” lights on the control panel

- Once the Contact Light illuminated, the CDR hit the “Engine Stop” switch, terminating DPS ops, and the LMP entered 413+1(0000) into the AGS and keyed PRO on the DSKY, which rolled the LGC into P68 (touchdown) and entered the landing coordinates into LGC memory for use on return to orbit

- In addition, the CDR pulsed the ACA to tell the LGC to not fire the RCS thrusters in response to any perceived non-level orientation precipitated by the slope of the landing surface

- Once that was completed, the crew ran through the post-landing checklist, safing the DPS, configuring the cockpit to either stay or immediately depart if there was an unsafe condition

- Note these callouts from Buzz Aldrin from Apollo 11:
    - *“Contact Light?...OK, engine stop…ACA out of detent…Mode Controls, Both AUTO… Descent Engine Command Overide OFF…Engine Arm OFF…413 is in.”*

Lunar Descent and Landing – Landing Phase

- Lunar surface directly below Apollo 11 DPS engine bell
- Notice the groove starting directly below the engine bell and going to the upper left
    - This is **the** spot where we first touched the Moon, caused by the initial contact and subsequent dragging of the lunar contact probe forward and to the left as the LM touched down with some residual lateral velocity

Lunar Descent and Landing – Summary

Flight Phase	LGC Actions	Crew Actions	Why Were We Doing It This Way?
Braking (PDI to High Gate, P63)	• Navigate to High Gate using state vector data derived from the platform to send appropriate commands to the DPS • Manage engine thrust to reach High Gate on the basis of engine limitations and platform and radar data • Manage LM C_g and moment of inertia changes with DPS gimballing and RCS firings • Provide appropriate H, H-dot, slant range and T_{GO} data to the crew	• Monitor the progress of the flight phase against pre-planned trajectory data • Act as “quality gate” for data coming into the LGC, such as Landing Radar data and NOUN 69 corrections • Monitor the vehicle for indications of degraded conditions that might lead to an abort	• The complexity of the phase was better managed by the LGC and monitored by the crew • The vehicle attitude through most of the phase precluded crew visibility of the lunar surface

Lunar Descent and Landing – Summary

Flight Phase	LGC Actions	Crew Actions	Why Were We Doing It This Way?
Approach (High Gate to Low Gate, P64)	• Provide LPD angles to show the targeted landing spot • Provide H and H-dot information • Accept redesignation data from the CDR's ACA • Manage engine thrust on the basis of both CDR inputs and P64 instructions	• LMP provides LPD angles, H, H-dot and lateral velocity data to the CDR • CDR uses LPD angles to manage the location of the LGC targeted landing spot	• The CDR's judgment of the quality of the LGC targeted landing spot is better than the LGC knowledge of the lunar surface

Lunar Descent and Landing – Summary

Flight Phase	LGC Actions	Crew Actions	Why Were We Doing It This Way?
Landing (Low Gate to Touchdown, P66)	• Based on the CDRs input, flying the LM as per the appropriate actions in P66 • Manage engine thrust on the basis of both CDR inputs and P66 instructions • For each Apollo flight, this meant using PNGCS Mode Control in ATT HOLD, with the ROD managing DPS engine thrust and the ACA controlling LM roll and pitch attitude	• CDR lands the vehicle using the ATT HOLD capability, the ROD to manage the vertical thrust, and the ACA to manage lateral velocity • LMP provides data on H, H-dot, and fuel remaining	• Each LGC-targeted landing spot was judged by the CDR to be too rough at an “LM-Footpad” scale, precluding allowing an automatic landing

Apollo Crew Experience –
How Did Each Landing Proceed?

Fly Me To The Moon…For Real

- There are really three histories of landing on the Moon – 1) Apollo 11, 2) Apollos 12 and 14, and 3) Apollos 15 through 17

- The Apollo 11 landing was really in a class by itself, largely because there were so many significant problems that were overcome by the aggregate team – the crew in the LM and the Flight Controllers on the ground – and which never happened again, or to the same critical extent they happened on Apollo 11

- Apollo 12 and 14 were, like Apollo 11, engineering flights, driven by either executing precision landing at a specific point (Apollo 12) or by landing in increasingly challenging terrain (Apollo 14)

- Apollo 15, 16 and 17 built on the earlier missions by precisely landing in challenging terrains (the lunar highlands, into narrow valleys, approaching right over high mountains) at sites that were critical for understanding lunar geology/ geophysics

- Each landing followed the approach described above, but each had elements that deviated from the "pure" approach procedure described above

Fly Me to the Moon
Apollo 11

Fly Me To The Moon – Apollo 11

- The Apollo 11 approach began with the LM executing the DOI burn on the lunar far side after executing an undocking from the CSM and an "inspection" maneuver where the CMP confirmed that the LM looked intact and ready to land
    - What we did not appreciate at the time is that various pre-PDI maneuvers and seemingly minute additions to thrust, such as residual tunnel atmosphere release and LM cooling water venting, were adding error to the approach path, leading to significant errors in the targeted landing spot

- The start of powered descent was nominal, and the Braking Phase proceeded as planned, although at MET 102:36:11 (T_{IG} +3 min 8sec) the LM passed a landmark target ≈3 seconds early, indicating it was going to land ≈ 3 mi long
    - Despite the navigational error, everything was still proceeding nominally

- At MET 102:38:04, the LM got good Landing Radar lock on the surface, which would provide H and H-dot data to the LGC after the crew and the ground agreed it was good data
    - At this point, Aldrin keyed in a VERB 16 (monitor digital data) and NOUN 68 (show slant range, T_{go} in P63 and the delta between the calculated state vector altitude and the Landing Radar data, called Delta-H)…and things started to get interesting…

Fly Me To The Moon – Apollo 11

- At MET 102:38:21, the delta-H data showed a 2900' delta-H difference between PGNCS calculated altitude and radar altitude, acceptable to continue powered descent

- At MET 102:38:26, the first program alarm happened, requiring Aldrin to do a VERB 5 NOUN 9 ENTER to display a 1202 Alarm Code on the DSKY
  - This alarm arose from the background EXECUTIVE program, which was running a myriad of jobs with different priorities related to the landing
  - EXECUTIVE was programmed to call a 1202 when there was no space left in the queue of jobs waiting to be calculated
  - This was particularly critical at this point, because the LGC is responsible for taking the raw radar data, converting it to digital data, integrating that into the state vector and showing corrected H and H-dot data on the DSKY
  - Without that calculation, the crew could not tell if the radar data was good, and subsequently could not tell the computer to accept the data into its calculations (a VERB 57 ENTER)
  - Armstrong chose to accept the data anyway, before the 1202 alarm evaluation was complete

Fly Me To The Moon – Apollo 11

- In what was a remarkable display of rapid thought and gutsy decision-making, only 16 seconds later, the Control Team decided that a 1202 Alarm would not jeopardize the landing, and CAPCOM Charlie Duke reported, "…we're go on that alarm!"
  - Prior to Apollo 11 launch, Kranz had given the team the assignment to understand every computer alarm that could come up, and to understand how to respond to them in flight (this was probably the most important pre-mission exercise that made the AS-11 landing possible)
  - Also, Aldrin recognized that the 1202 happened when the V16 N68 was executed, suggesting to him that it was somehow related to the additional computations required by those actions
  - The actions by the Flight Control Team would later earn them a Presidential Medal of Freedom

- At MET 102:39:34, DPS went though the planned throttle down to <60%, exactly on time and to the correct throttle setting

- At MET 102:41:35, the LGC switched over to P64, and the LM pitched over so the crew could assess the landing site using LPD angles
  - At this point, H was ≈5,000 ft and H-dot was 100 ft s-1, which placed the minimum Abort/Stage altitude at ≈1,100 ft
  - At MET 102:42:05, Armstrong took the PGNCS Mode Control switch from AUTO to ATT HOLD to check how the LM responded, and then went back to AUTO…this was going to be critical over the next 4 minutes

Fly Me To The Moon – Apollo 11

- Then, at MET 102:42:17 with the LM at 3,000 ft, the first 1201 alarm sounded
  - CAPCOMM Duke immediately called, “Roger…1201 Alarm…we’re go, same type, we’re go”, and the crew continued descending
  - As it turns out, the 1201 was only one of the critical things going on

- At MET 102:42:32, Armstrong saw West Crater looming large in his window and called for an LPD from Aldrin
  - Initially, the targeted landing spot looked good, but at MET 102:43:10, about 40 seconds later, Armstrong realized that the LGC-targeted landing spot was unacceptable due to large boulders on the West Crater ejecta blanket

- At MET 102:43:15, Armstrong took over control of the vehicle, selecting PGNCS ATT HOLD on the Stability and Control panel
  - Armstrong then “bumped” the system into P66 by pulsing the Rate of Descent (ROD) switch, and started pulsing the ACA (rotational hand controller) forward
  - This started the LM flying down range, beyond West Crater to a more suitable landing site
  - At this point H was 600 feet, H-dot was 19 ft s^{-1}

Fly Me To The Moon – Apollo 11

- At MET 102:43:26, the LM was down to 500 ft with a forward velocity at 58 ft s^{-1} forward and an H-dot was 15 ft s^{-1} down
  - The forward velocity was almost 40 mph, and 16 seconds later, Aldrin reported that the forward velocity on the velocity cross pointer display was “pegged”
  - Although it’s not like a fighter buzzing the tower (despite what is shown on various Discovery Channel specials), Neil *has* placed the LM in an attitude where the descent angle has decreased considerably and the LM has a larger horizontal vector component to allow them to move across the surface
  - Note that at this point, the Abort/Stage boundary is ≈230 ft

- At this point, Armstrong has gone off script and is aggressively flying the LM downrange in P66 - PGNCS-ATT HOLD, using the ACA to pitch the LM over and give it more forward velocity
  - Although the flight controllers had no idea what was going on, to the Flight Director’s and control team’s credit, they stood by to assist and let the crew fly the LM

Fly Me To The Moon – Apollo 11

- At MET 102:43:46, Armstrong reduced his pitch angle to slow the LM up in preparation for landing
  - Throughout this evolution, Aldrin has been giving him constant updates on H, H-dot and horizontal velocity so Armstrong could stay out the window, finding an acceptable landing spot
  - Without Aldrin's input, Armstrong would have a limited idea of the LM H, H-dot and lateral velocity, and it is unlikely he would have been unable to continue the approach without looking in the cockpit and losing lock on where the LM was with respect to the landing spot

- At MET 102:44:04, Aldrin reported seeing the shadow of the LM

- At MET 102:44:45, H was 100 ft, H-dot was 3 ½ ft sec^{-1} down, forward velocity was 9 ft sec^{-1} and fuel was down to about 8% - they were getting very close to a "Bingo fuel call"
  - This meant they were committed to landing, as they were below the safe Abort/Stage boundary

- At MET 102:45:31, CAPCOMM Duke called 30 seconds of fuel remaining
  - H is 20 ft, H-dot is ≈ ½ ft sec^{-1}, and forward velocity is 4 ft sec^{-1}

- At MET 102:45:40, Aldrin called "Contact Light", Armstrong hit the Engine Stop pushbutton, and the LM dropped the last few feet to the surface

Fly Me To The Moon – Apollo 11 Assessment

- There has been a lot of ink spilled over what happened on Apollo 11, particularly in terms of the significance of the 1202/1201 alarms, and I'm most likely not going to illuminate that discussion

- The cause of the alarms has been debated a lot, but based on Don Eyles and the Draper Lab experience, it appears that the likely "first order" cause was an issue with the Rendezvous Radar, particularly getting incompatible data from Rendezvous Radar when the LM panel switch was in either SLEW or AUTOTRACK
  - This led the LGC to what I would (irreverently) call Whiskey Tango Foxtrot response as it tried to handle the data, could make no sense of it, and still tried to work with it, stealing the limited RAM that was left in the LGC after calculating the state vector every 2 seconds
  - Even then, in other phases, the spurious activity would not have been a problem… except when you were doing the most difficult task of the mission, landing on the Moon
  - Ironically, this had been seen in testing, but only 2% of the time, and it was considered low enough probability that it shouldn't occur in flight…except that it did

- The good news is that it was a simple fix, ensuring that the incompatible data issue never happened again

Fly Me To The Moon – Apollo 11 Assessment (cont.)

- I think an equally important part of the discussion is the response of the crew and the MOCR team
  - First and foremost, the crew kept flying in spite of hub-bub, although responding to the problem dominated what would have been time devoted to flying a nominal approach
    - *"Normally …from P64 onward, we'd be evaluating the landing site and checking our position and starting LPD activity. However, the concern here was not with the landing area we were going into but, rather, whether we could continue at all (because of the program alarms). Consequently, our attention was directed toward clearing the program alarms, keeping the machine flying, and assuring ourselves that control was adequate to continue without requiring an abort. Most of the attention was directed inside the cockpit during this time period and, in my view, this would account for our inability to study the landing site and final landing location during the final descent. It wasn't until we got below 2000 feet that we were actually able to look out and view the landing area."* [Neil Armstrong, from the Apollo 11 Post-Mission Technical Debrief, quoted after MET 102:42:35 on the Apollo 11 ALSJ landing page]
    - The bottom line is they kept their cool, kept flying the vehicle and kept their faith in the machine, the systems and the folks on the ground
  - In the MOCR, they were able to decide in 16 seconds that the landing could continue, particularly with the help of Jack Garmin, Steve Bales, Draper Lab's Russ Larson and various back room controllers
    - This was largely due to Kranz's assignment to find out and understand every possible alarm code that could come up on the LGC during landing
  - This speaks to the value of the extensive training the whole team had prior to Apollo 11, and the robustness of the LM, the LGC, and the humans in the loop to deal with a problem that might have otherwise called an abort

Fly Me To The Moon – Apollo 11 Assessment (cont.)

- The other critical event on Apollo 11 is Armstrong's response to the auto-targeting taking him into a spot where safe landing of the LM was in question

- This is (again, at least to me) the best example of "Pilot-in-Command" actions in the Federal Aviation Regulations Part 91.3 sense
  - Armstrong saw, using the LPD angles, that the LM was headed for an unsafe spot, with only limited options
    - To land short meant they would have to increase their rate-of-descent, which might have been possible, but would have been very sporty
      - *"As we approached the 1500-foot point, the program alarm seemed to be settling down and we committed ourselves to continue. We could see the landing area and the point at which the LPD was pointing, which was indicating we were landing just short (and slightly north) of a large rocky crater surrounded with the large boulder field with very large rocks covering a high percentage of the surface. I initially felt that that might be a good landing area if we could stop short of that crater, because it would have more scientific value to be close to a large crater. (However), continuing to monitor the LPD, it became obvious that I could not stop short enough to find a safe landing area." [Neil Armstrong, ALSJ entry, MET 102:42:35]*
    - West Crater was to the left (south) of the LM's path, so that was no good, and to the right (north), the LM would still be flying into the West Crater ejecta blanket
  - The only real option was to fly downrange, which he did

- Having a pilot aboard, able to take over and fly to a safe spot, was the key to success on Apollo 11, and without Armstrong having the option to do that, Apollo 11 would have either ended in a very bad day (LM crash, LoC, LoM) or a very unsatisfying failure (LM aborts home, no landing on Apollo 11…maybe no landing before the decade was out…)

Fly Me to the Moon
Apollo 12

Fly Me To The Moon – Apollo 12

- If everything that *could* go wrong with the LGC and the navigation *went wrong* on Apollo 11, then everything that could go right with the same systems went right on Apollo 12

- Apollo 12's main objective was to demonstrate not only that the LM could land safely on the Moon, it could land with pinpoint accuracy at a location that was important for both science and spacecraft engineering
    - The key science objective was to visit another mare site to compare the returned samples with the Apollo 11 samples
        - Another key science objective was to emplace the first geophysical station, the Apollo Lunar Scientific Experiment Package (ALSEP), which had been left off Apollo 11 due to weight and crew EVA time considerations
            - The ALSEP array on Apollo 12 weighed in at >175 pounds (≈85 kg), which represented seconds in hover time
            - In addition, the crew time necessary to deploy the package (3-4 hours) would exceed the planned Apollo 11 EVA time
        - Both of these objectives could have been accomplished without precision landing
    - The key engineering objective was to return samples of the Surveyor III spacecraft, which had been on the Moon for ≈2 ½ years
        - Given the limitations of walking EVAs, this dictated that the LM had to land <1 km from the Surveyor

Fly Me To The Moon – Apollo 12

- As with Apollo 11, the DPS performed the DOI burn while on the lunar farside at MET 109:23:29
  - Unlike Apollo 11, the Apollo 12 crew went to great pains to minimize *any* spurious delta-V inputs (one MPAD memo indicated even urine dumps would be enough to screw up the trajectory…) during the runup to DOI
  - The DOI burn put the LM into a 60.5 nm by 8.9 nm orbit, with minimal residuals and good agreement between AGS and PGNCS, which was the first step to a precision landing

- At MET 109:50:52, the ground updated the LM state vector and then, based on these data, updated the AGS in preparation for executing the Powered Descent burn

- At MET 110:13:38, Conrad enters a VERB 50 NOUN 18, which puts the LM in the proper attitude for P63 PDI

- At MET 110:20:06, the LGC signals it is running the Average g program by a momentarily blank DSKY

- At MET 110:20:29, the LM started PDI on time, with throttle up 26 seconds later

Fly Me To The Moon – Apollo 12

- At MET 110:21:57 , ≈1 min 30 sec into Powered Descent, the crew and the ground implemented the DLAND trajectory correction on the basis of MSFN tracking data, which gave them an opportunity early in Powered Descent to correct any trajectory issues with a "fudge factor" that would bring the LM to its planned landing spot
  - As noted earlier, DLAND was not available on Apollo 11
  - Entering the appropriate data in DLAND, a NOUN 69, was critical to a good approach – entering the incorrect data was a serious problem, so ENTER was only pressed after both the crew and the ground agreed on the value to be entered
    - Unlike most air-to-ground exchanges, which were pretty terse, the NOUN 69 confirmation and execute discussion took ≈30 seconds, indicating the interaction necessary to confirm it was entered correctly
  - In this case, the NOUN 69 value entered was +4200 ft in the downrange direction, with no correction required for left or right retargeting
  - The entry string was VERB 21 NOUN 69 ENTER – the VERB 21 told the LGC that it was only a downrange correction (Register 1 on the DSKY; Register 2 and 3 are crossrange and altitude, which were not changed)

Fly Me To The Moon – Apollo 12

- At MET 110:23:58, the Altitude and Velocity lights on the DSKY went out, indicating that the Landing Radar had good lock on the surface
  - The Delta-H comparison (≈900-1,000 ft) was considered good, so at MET 110:24:26, Landing Radar was incorporated into the LGC calculations

- Pretty much all through the initial part of Powered Descent, everything went nominally (one might say, "nominal in the extreme"…)
  - PGNCS and AGS agreed, sometimes with zero residuals, engine performance was right to spec, and about the only crew comments were a significant number of RCS firings, something that did not happen in the simulator, something seen on Apollo 11 as well
  - The RCS activity would later be found to be caused by fuel and oxidizer sloshing in the prop tanks, which did not have anti-slosh baffles
    - After Apollo 12, Grumman would undertake a very delicate "ship-in-a-bottle" modification to the prop tanks (which had already been delivered for each LM) that welded anti-slosh baffles through the tank mouth
    - This solved the problem on future landings

- Throttle down (throttle recovery) occurred at MET 110:27:07, at T_{ig} +6 min 26 secs, which was immediately followed by another AGS update
  - At this point, everything was completely nominal, in comparison to Apollo 11

Fly Me To The Moon – Apollo 12

- At MET 110:29:10, the LGC picks up running P64 and the LM pitches over to give the crew the first view of the landing site
  - I printed the transcript earlier, so I won't repeat it here except for one callout that seems to sum up the Apollo 12 descent to landing:
    - **MET 110:31:06** Bean*: Hey! Look at that crater; right where it's supposed to be!*
    - During pre-flight planning, Conrad decided to use as the LM aim point the center of Surveyor crater, assuming that the guidance would never be that precise – to his chagrin, the rest of the Approach Phase and the Landing Phase were spent moving the touchdown point so they *didn't* land right in the middle of Surveyor Crater

- From this point until the start of the Landing Phase, Conrad uses numerous LPD angle callouts from Bean to redesignate the landing point away from the center of Surveyor Crater
  - During P64, Conrad will make seven redesignations of the landing point before switching into P66
    - *Conrad, from the 1969 Technical Debrief - "I gave her one click forward, let her go for a while, and decided that we were high and fast. I didn't like the size of the area short, where we had normally been trying to land, and I looked for a more suitable place. ('That much I remember,' Pete said [during Eric Jones' interview for the ALSJ] in 1991.)"*

  - During the same time, Bean will make continuous callouts on LPD angle, H, H-dot and fuel state to keep Conrad apprised of the condition of the vehicle and where it's going
    - **MET 110:30:08** Bean*: "38 (degrees on the window). 38 degrees. 36 degrees; you're 1200 feet, Pete. A thousand feet coming down at 30 (feet per second). You're looking good. Got 14 percent fuel. (Glancing out the window, again) Looks good out there, babe. Looks good! (Pause) 32 degrees. You're at 800 feet. 33 degrees. You're at 680 feet. 33 degrees, 600 feet."*

Fly Me To The Moon – Apollo 12

- At MET 110:30:52, at an altitude of ≈500 ft, Conrad switched the LM into P66 and proceeded to fly the landing in a “manual mode”
    - I use the quotes because at this point in the evolution of LGC programs, there were 3 modes the crew could land in:
        - P65 – “Pure” automatic mode – the LGC would null out lateral rates, and then gradually reduce thrust until lunar contact
        - P66 – A manual mode where the vehicle is PGNCS Mode – AUTO HOLD, and the CDR uses the ROD switch to manage the rate-of-descent while the LGC holds the vehicle attitude steady automatically
        - P67 – “Pure manual mode”, where the LGC is taken out of the loop and the CDR is commanding DPS thrust with the TTCA and the attitude, and the DPS thrust vector, with the ACA
    - Other than a “P66” call, there was never an “ATT HOLD” call or an indication Conrad is using the ROD switch, but in the absence of the call to P65 or P67, I’m reasonably sure they’re in the mode that all other landings used

- From here until touchdown, Conrad is flying the LM around Surveyor Crater to an acceptable spot on the NW side of the crater, while Bean continues to give him cues on H, H-dot and fuel
    - **MET 110:31:06** Bean*: Hey! Look at that crater; right where it's supposed to be! Hey, you're beautiful. Ten percent (fuel remaining). 257 feet, coming down at 5; 240 coming down at 5. Hey, you're really maneuvering around.*
    - **MET 110:31:21** Bean*: Come on down, Pete.*
    - **MET 110:31:23** Bean*: Ten percent fuel. 200 feet; coming down at 3…’need to come on down.*
    - **110:31:31** Bean*: 190 feet. Come on down. 180 feet; 9 percent (fuel remaining). You're looking good. Going to get some dust before long. 130 feet; 124 feet, Pete. 120 feet, coming down at 6. You got 9 percent, 8 percent. You're looking okay. 96 feet, coming down at 6. Slow down the descent rate! 80 feet. 80 feet, coming down at 4. You're looking good. 70 feet; looking real good. 63 feet. 60 feet, coming down at 3.*

Fly Me To The Moon – Apollo 12

- By MET 110:32:06, Conrad nulled out all the lateral motion, and was probably managing H and H-dot down to the landing spot using the ROD switch – in other words, he was flying as per the P66 landing program, not P65 or P67
  - *Conrad, from the 1969 Technical Debrief - "At that point, the dust was bad enough and I could obtain absolutely no attitude reference by looking at the horizon and the LM. I had to use the 8-ball [DE-Note: the Flight Director Attitude Indicator an "artificial horizon")]. I had attitude excursions in pitch of plus 10 (degrees) and minus 10, which happened while I was looking out the window making sure that the lateral and horizontal velocities were still nulled. I would allow the attitude of the vehicle to change by plus or minus 10 degree in pitch and not be aware of it, and I had to go back in the cockpit and keep re-leveling the attitude of the vehicle on the 8-ball. I was on the gauges in the cockpit doing that at the time the Lunar Contact light came on. I had that much confidence in the gauges. I was sure we were in a relatively smooth area."*

- At MET 110:32:35, Bean called "Contact Light", and Conrad hit the Engine Stop button, dropping from ≈3 ft to the lunar surface

Fly Me To The Moon – Apollo 12 Assessment

- Apollo 12 performed an essentially flawless landing on the lunar surface, demonstrating that all of the issues that were raised during the Apollo 11 landing had been fixed, and that while landing would never be “routine”, the LM systems and the crew performance should allow further, more challenging landings to proceed
  - Conrad showed that while blowing lunar regolith can obscure the landing site in the final stages of touchdown, using the instruments and settling in with minimal lateral movement would still give you a safe touchdown evolution.

- In a way, Apollo 11 and 12 were “bookends” – one flight showing that you could land on the Moon, but all kinds of systems needed to work flawlessly, and one flight showing that, if the systems worked flawlessly, you could go wherever you wanted to

- The crew would go on to do two EVAs, deploy the first ALSEP, bring back samples that were significantly different from Apollo 11, and bring back pieces of the Surveyor spacecraft to show how the lunar environment treats man made structures
  - The Surveyor parts are still the only man-made structures brought back from the lunar surface, and their condition and history should still inform lunar surface system design work

Fly Me to the Moon
Apollo 14

Fly Me To The Moon – Apollo 14

- Given the success of Apollo 12, Apollo 13 was set to land in the first "topographically" challenging area near the crater Fra Mauro, which was characterized by low, rolling hills, in contrast to the flat maria sites on Apollo 11 and 12

- After Apollo 13's abort, it was decided that the Fra Mauro site was still critical for lunar science, so Apollo 14 was targeted for the same landing site

- Apollo 14 was also the first mission where the shift in DOI "responsibility" to the CSM was implemented

- The CSM-LM stack successfully entered orbit at MET 81:56:42 into a 58.4 nm by 169 nm orbit, which was the orbit planned to stage the stack for the DOI burn

- The DOI burn came ≈4 hours 8 minutes later at MET 86:10:53, which put the stack in a 9.1 nm by 58.4 nm orbit

Fly Me To The Moon – Apollo 14

- LM undocking came at MET 103:47:52 – undocking was nominal, but then things started to get interesting…
    - As the LM was going through the pre-PDI checks, the ground noticed that it was getting data that suggested that the LM abort discrete was being set, automatically and incorrectly, without crew input
        - A "discrete" was a signal in the LGC that , while not an "automatic abort trigger", was an indication that an inadvertent abort during Powered Descent was a significant possibility
            - Basically, every 0.25 seconds the LGC Abort Monitor Routine would verify that an abort signal (the LETABORTBIT Flag) was set in the LGC
            - Positive verification would lead to a check of the discrete, and if both bits were positive, the LGC would automatically command either an Abort (P70) or Abort/Stage (P71)
    - The crew tapped on the abort button, which caused the discrete to go on and off, suggesting that a piece of FOD in the switch was causing a short and triggering a false discrete signal
        - The concern was that during PDI, the acceleration would move the FOD into the switch and trigger an automatic abort without crew input

Fly Me To The Moon – Apollo 14

- At first, Don Eyles (who wrote the original code) thought that the LETABORTBIT flag could be programmed off, which would disallow automatic aborts, but would still allow the crew to manually abort if necessary
    - This would have used a NOUN 5 to spoof the LGC into shutting off the LETABORTBIT flag
    - However, a closer inspection of the code showed Eyles that while the LETABORTBIT was normally off preceding DPS ignition, it would automatically (spoofing notwithstanding…) reset at PDI/$T_{ig} = 0$, regardless of the pre-existing NOUN 5, making it likely an abort would be triggered before the crew could intervene and re-execute the NOUN 5

- At this point, it was realized that a whole new program sequence needed to be written by Eyles, tested in the simulator, validated, verbally sent up to the crew (there was no printer on board during Apollo), entered by Mitchell, all in <4 hours so they didn't miss a second shot at the Fra Mauro landing site

- Essentially, Eyles made the computer believe, during P63, that a P71 abort was already in progress (even though it wasn't…)
    - This used a register called MODREG, which kept track of which program was actually running
    - To quote Eyles directly, *"Setting MODREG to 71 during 63 seemed radical, but perhaps it was not as dangerous as it sounded. It would not actually initiate the abort programs… BURNBABY – the master ignition routine…was calling the shots, and the paths taken by BURNBABY were controlled by a parameter independent of MODREG. Mostly."* [Don Eyles, "Sunburst and Luminary, pg. 257]

Fly Me To The Moon – Apollo 14

- BTW, if about now, you're thinking, "Holy [*insert your favorite expletive here*]!", you're not alone – I think this was the most critical moment in any lunar landing other than Apollo 11

- In the end, the crew had to execute the following sequence:
  - To set up the cockpit, the Mode Control Switch was set to ATT HOLD, the Throttle Control Switch on the Thrust Control Panel was set MANUAL
  - After the DSKY started counting down to P63, but before ignition, the LMP keyed in VERB 21 NOUN 1 ENTER 1010 ENTER 107 ENTER
    - This would set the mode register to 71 (abort in progress) with the address of MODREG = 1010, with 107 being the octal code for P71
  - At exactly T_{ig} = +26 seconds, the CDR manually pushed the TTCA to throttle to 100%
  - At completion of throttle up, the LMP keyed in VERB 25 ENTER NOUN 7 ENTER 101 ENTER 200 ENTER 1 ENTER
    - This reset ZOOMFLAG and enabled landing guidance equations supporting LGC ops
  - Next, the LMP keyed in VERB 25 NOUN 7 ENTER 105 ENTER 400 ENTER 0 ENTER, which would immediately disable the LETABORTBIT abort flag
  - Finally, the LMP keyed in VERB 21 NOUN 1 ENTER 1010 ENTER 77 ENTER, which set the program register back to P63
  - Finally, the CDR reset the Throttle Control and Mode Control switches to AUTO, returning the throttle to MIN, leaving the LGC in charge of throttling DPS automatically during P63 (which was back to happily managing Powered Descent)

- A downstream effect of this "spoofing" was that any aborts would have to be manually initiated and run on the AGS, including an immediate abort from the surface

Fly Me To The Moon – Apollo 14

- At MET 108:02:26, the crew initiated Powered Descent
  - Manual throttle up was executed by Shepard at T_{ig} +27.25 seconds (only 1¼ seconds late…), and Mitchell proceeded to upload the remaining command strings into the LGC to spoof the LM into continuing the descent
    - The various DSKY strings were uploaded by MET 108:03:57, and the Braking Phase proceeded nominally from there on…well, almost…(remember that a critical, mandatory abort happens if the crew does not get Landing Radar returns, confirm a good Delta-H comparison, and tell the LGC to accept radar data by 30,000 ft…)

- At MET 108:04:50, the crew executed the DLAND targeting correction by entering a NOUN 69, with a downrange correction of +2800 feet
  - This would ultimately enable the surface science ops after the landing by ensuring the crew landed at the spot from which the planned EVAs originated

- At MET 108:08:16, 6 mins 40 secs into Powered Descent and down to 32,000 ft, the Altitude/Velocity lights were still lit, indicating that the Landing Radar was not locked onto the surface
  - By the time they were below 25,000 ft, they still did not have radar data, and things were looking dicey

Fly Me To The Moon – Apollo 14

- At MET 108:08:42, CAPCOMM Haise directed the crew to recycle the Landing Radar circuit breaker, and it worked
  - At MET 108:09:14, Shepard reported that the Altitude/Velocity Lights were out, and the approach proceeded
    - **MET 108:09:39** Mitchell*: "Great. Whew; that was close*."
  - It was shown later that either an unexpectedly strong return from the surface or a side lobe bouncing off of LM structure had switched the radar into short range mode, which prevented lock up until that circuit breaker was cycled

- The rest of the approach (PGNCS-AGS agreement, DPS throttle down) was completely nominal, in contrast to the other excitement during the early parts of Powered Descent

- At MET 108:11:13, the LM went into P64 and pitchover occurred right on time, with Shepard immediately sighting Cone Crater, the major science target of EVA 2

- The LMP immediately began giving LPD angles; the agreement between the planned landing site and the guidance was very good, and Shepard only redesignated once during P64

Fly Me To The Moon – Apollo 14

- At MET 108:13:05, Shepard pushed the LGC into P66 by switching the PGNCS Mode Control Switch to ATT HOLD and pulsing the ROD several times, and proceeded to drive the LM to his planned landing site
- At MET 108:13:24, Shepard leveled the LM, nulled out his lateral velocity, and began letting the LM down to his selected landing spot
- At MET 108:14:52, CAPCOMM Haise made the 60 seconds to Bingo Fuel call
- At MET 108:15:11, Mitchell called the Contact Light, and the LM landed at MET 108:15:12 after Shepard hit the Engine STOP switch
    - At landing, the LM was moving ≈3 ft s^{-1} down, forward at about 2 ft s^{-1}, and left about 1 ft s^{-1}
    - In addition, the LM was <60 ft from the planned landing spot, which was critical, as this crew had the longest walking EVAs on Apollo

Fly Me To The Moon – Apollo 14 Assessment

- Apollo 14 would probably have to abort the landing (and potentially doom the subsequent 3 flights of Apollo) if it wasn't for three key personnel
  - The first is, obviously, Don Eyles, whose knowledge of the software made it possible to quickly understand the problem, understand the work-around quickly enough to write a new code sequence, test it and find lurking bugs, and then complete the procedural change sequence and get it radioed up to the crew in time to do a successful landing
  - The second is Ed Mitchell, who from the start of his participation in Apollo had specialized in the LM and its subsystems, particularly the LGC, making him one of the most knowledgeable astronauts about the vehicle
  - The third is Fred Haise, who had a similar level of understanding of the LM and in his role as CAPCOMM, was able to understand and call up the procedure for spoofing the LGC so Mitchell could implement it
    - *"I was on the backup crew for [Apollo] 10. Also, I'd been on the support crew for [Apollo] 9. Fred Haise and I probably knew more about the lunar module than any two guys alive at that point, since we helped build it at Grumman/Bethpage (the facility at Bethpage, New York, where the LMs were designed and built). And had been through all the cycles with all the spacecraft - with all of the lunar modules." Ed Mitchell, ALSJ debrief comments after MET 106:38:13.*
  - Without all three of these guys, it is unlikely Apollo 14 would have been successful

Fly Me To The Moon – Apollo 14 Assessment

- Apollo 14 also points out the need to get into the code and be able to rewrite it in real time to meet a short-timeline contingency
  - Regardless of the talents of the crew, the MOCR team and the software folks, it would have been for naught if they were unable to figure out a solution, and unable to implement it in real time

- The Landing Radar issue shows that even with simple fixes (cycling a switch) can work in a pinch
  - Ed Mitchell's, "…whew, that was close" comment when they had good Landing Radar data was spot on!
  - Lack of Landing Radar data would have meant a mandatory abort, which would have been doubly frustrating after all the work to get them to PDI
  - The Apollo 14 crew was very lucky, particularly that the Landing Radar data fix (cycling the circuit breaker) was simple compared with the code strings that Mitchell had to upload while the Braking Phase was underway

- Lastly, the ability to land as close to the planned touchdown spot was critical to completing the science objectives, given that the Lunar Roving Vehicle (LRV) was not available until Apollo 15
  - As it was, Apollo 14 EVA 2 was the most physically challenging of all the Apollo EVAs, with the largest metabolic rates during Apollo, due to the difficulty of walking uphill in the A7L pressure garment

Fly Me to the Moon
Apollo 15

Fly Me To The Moon – Apollo 15

- Apollo 15, 16 and 17 jointly comprised the "J-missions" – missions that included an upgraded LM (often referred to as a "Block II LM") with more delta-v, an extended DPS engine bell and the capability for increased downmass

- These upgrades allowed the LMs to carry sufficient consumables for three days on the lunar surface, and the ability to carry a Lunar Roving Vehicle (LRV), which increased the crew's range of travel from no more than ≈2 km to as far as 10 km away from the LM

- Making good use of these capabilities for exploration dictated the need to land in more challenging terrains – approaching over some of the steepest mountains on the Moon, landing in the highlands, and landing into relatively narrow alpine valleys

- The Apollo 15 mission was the first to test these capabilities, landing at a maria site in western Mare Imbrium that would require an approach over the Apennine Front, which had a maximum altitude of ≈15,000 ft and a 12,000 ft ridgeline that the LM approach path crossed over at 22,000 ft
    - Because of the terrain clearance considerations, Apollo 15 approach path from pitchover to touchdown would be twice as steep as the earlier landings

Fly Me To The Moon – Apollo 15

- LM undocking came at MET 100:39:37, about 20 minutes late due to a minor issue with the CSM probe umbilicals which CMP Worden had to take care of prior to undocking
  - Otherwise, undocking and separation was nominal, and the CDR (Scott) and the LMP (Irwin) went through normal pre-PDI checks, including helping CMP with prep and execution of the CSM circularization burn

- At MET 104:09:14, about 20 minutes prior to PDI, the crew put a 3.3 nm "south to north (left to right)" correction into the LGC using a NOUN 61, based on MSFN tracking data; this meant that sometime during PDI, the LM would yaw to change the DPS thrust vector to put in that correction
  - *"This was important, but an MCC input which did not affect the final descent from our perspective in the LM. If MCC made the call at this point, we complied without hesitation, MCC "flew" the vehicle (had the stick) until pitchover (and then we had the stick)."* [Dave Scott, e-mail to Eppler, 2 January 2020]

- PDI occurred at MET 104:30:12, with nominal engine sequencing and performance
  - The Braking Phase proceeded nominally throughout, with a DLAND/NOUN 69 downrange correction to the trajectory of 2800 ft about 1 min 30 sec into the burn
  - At about 3 minutes into the burn, the LM yawed right to "pure face up" to correct an earlier left yaw to get better comm coverage earlier in Braking Phase

Fly Me To The Moon – Apollo 15

- At MET 104:33:25, the Altitude/Velocity lights went out, and the Delta-H calculation (3400 ft difference) was acceptable, allowing the crew to accept Landing Radar data into the LGC

- At MET 104:38:38, about 10 secs prior to pitchover, Scott began to see the mountains in the lower corner of his window at an H of ≈9,000 ft

- At about MET 104:39:00, the MOCR determined that the LM was targeted south of the planned landing spot by ≈3,000 ft;
  - Although the Flight Director originally was against relaying that information to the crew, Ed Mitchel, the CAPCOMM, felt it was important to keep Scott and Irwin apprised and shortly relayed that data
  - **104:39:17** Mitchell: *"Falcon, Houston. We expect you may be a little south of the site, maybe..."*
  - **104:39:18** Irwin: *"Okay. Coming up on 8000 (feet altitude)."*
  - **104:39:19** Mitchell: *"...3000 feet."*
  - **104:39:24** Scott: *"(Responding to Mitchell) Okay."*
    - *"As noted from this exchange, during final descent, MCC told us we were about 3,000 feet south of the planned touchdown point. So, immediately after pitchover, I began moving us north with the LPD. However, when I could finally identify some landmarks, I realized we were going too far north, and began to move us back south with the LPD. Eventually we got pretty close to the original target point. But lo and behold, when we received the 3,000 ft south call, the state vector trajectory had already been corrected for the 3,000 feet; therefore, we were actually on the correct trajectory when we got the 3,000 feet north call - that is, MCC made a double correction. See page 253 and Note 58, page 300, in Digital Apollo. This double correction plus the simulator confusion (also in Digital Apollo), made the selection of a touchdown point quite a challenge....!!* [Dave Scott, e-mail to Eppler, 2 January 2020]

Fly Me To The Moon – Apollo 15

- At MET 104:39:32, the LGC hit the P63 T_{go} of zero and rolled over into P64, initiating pitchover at High Gate
  - The Braking Phase took almost a minute longer than on previous flights due to the increased weight of the upgraded LM
  - *Scott, from the 1971 Technical Debrief - "When we pitched over, we got P64 right on time…I couldn't convince myself that I saw Index Crater [a key landmark – DE] anywhere. I saw, as I remember, a couple of shadowed craters, but not nearly as many as we were accustomed to seeing (in the LM simulator)...We were south, and I redesignated immediately (with the LPD) four clicks to the right (north) and then, very shortly thereafter, after [Irwin] called me again on the LPD numbers, I redesignated two more right and three uprange...*
  - *Scott, from the 1971 Technical Debrief – "I got busy, at that time, attempting to select a point for the actual landing. I guess our pre-flight philosophy had been that, if we were on target, we would try to land exactly on target. If we had a dispersion, we would select some point within the 1-kilometer circle which looked like a good place to land and (then) would land as soon as possible so as not to get behind in the propellant curve. Once I realized that we were not heading for the exact landing site, and that I didn't have a good location relative to Index Crater, I picked what I thought was a reasonably smooth area and headed directly for that." [ALSJ, multiple integrated comments, quoted after MET 104:40:28]*
  - As noted earlier, Scott would go on to make 18 total redesignations, more than any other landing

Fly Me To The Moon – Apollo 15

- At MET 104:41:08 and at H=400 ft, Scott switched the LGC into P66 and began to set up for touchdown

- At MET 104:41:51 (H=60 ft), blowing dust began to obscure the landing spot
  - At this point, Scott largely nulled his lateral velocity and brought the LM down to the surface with ROD switch pulses
  - Scott's situational awareness was largely coming from Irwin's crisp annunciation of LM attitude and velocity data, based on LGC and cockpit instruments
    - ALSJ Comment by Scott after MET 104:41:54: "*I was still [looking] outside. We had trained enough that Jim would call anything to me that didn't look exactly right. And he would call the things that I wanted that looked right. So what he was telling me is something I would have normally looked at, at the last moment, to check myself. In the dust, I can't see whether we're going this way or that way. I could have looked at them [the Cross Pointer Instrument showing lateral velocities- DE]. But I didn't have to look at them because he did it for me, 'cause he knew I wanted to look at them, and I knew he knew what he was looking at.*"

- At MET 104:42:29, Irwin called the Contact Light on, and Scott immediately hit the Engine Stop Switch
  - **MET 104:42:29** Irwin*: "Contact. (Pause) Bam!" [ALSJ callout]*
    - *Irwin - "We did hit harder than any of the other flights! And I was startled, obviously, when I said, 'Bam!' " [ALSJ callout after MET 104:42:29]*
    - *"As noted [in the ALSJ – DE], we landed in on a crater rim. "Contact" by the +Z (forward)and +Y (right) footpads and by Jim's call was at 1 fps (target rate), but was actually was at 0.5 fps; this was followed by the other footpads (-Y (left) and –Z (aft)) into the crater (as the LM rotated about 4 feet into the crater to final "touchdown" at which the descent rate was 6.8 fps (thus the firm impact of the final legs). This resulted in a final tilt of about 11 degrees. The crater was about 5 feet deep and 15 to 25 feet across. The descent engine was shutdown immediately upon contact due to the anticipated pressure buildup inside the lengthened engine bell and potential backpressure into the descent stage (unlike e.g., A-12 when Pete counted two seconds until he shut the engine down)."* Dave Scott e-mail to Eppler, 2 January 2020.

Fly Me To The Moon – Apollo 15 Assessment

- The approach to landing on Apollo 15 was about as nominal as you could get – in fact, the discussion between the crew and the ground, and between Scott and Irwin, was so casual that you would think they were shooting a VFR straight-in approach to Ellington Field

- First, I think this is an outcome of Scott spending a lot of time talking to the previous crews and thinking about how he would fly the approach
  - Scott ALSJ comment after MET 104:42:48*: "Another objective we had, based on the previous flights, was to stay on a constant flight path - a constant rate of descent - and get it down. The previous flights…had all leveled out high and then had come back down. And we looked at their trajectories, and it seemed to be a trend, that the guys would start stopping too soon and use up a lot of propellant, doing a stairstep thing. So one of the things that we trained on and thought about, was to keep it going and keep it coming down a constant flight path so that we could save gas for the hover, if we needed it. The stairstep appeared to be a trend that people got into because there's no definition on the ground. There's no runway…There's nothing there to tell you how high you are; and I think the trend had been for people to start slowing up their rate of descent too soon - because, of course, you don't want to get too close, too fast, 'cause then you can't stop."*

  - Watching the cockpit view from High Gate to landing, the approach to landing is marked by a continuous descent right to the surface (it's *actually* a little scary to watch), with little hesitation in either the approach angle or descent rate, right down to the P64-P66 transition

Fly Me To The Moon – Apollo 15 Assessment

- Second, I think Scott and Irwin spent a lot of time working out their "cockpit protocol": who would do what, the data they would exchange, how they would communicate, and then trained the approach *exactly* as they would fly it
  - Scott ALSJ comment after MET 104:42:48*: "As I recall, I went out the window as soon as we got down there (that is, at pitchover). Everything inside is for Jim. For me to come in and go back out, really takes too much time…I wanted as much from Jim as I could get. I mean, I was outside the window. Everything from inside the cockpit was from Jim. So I had a lot of sources of information…So when Jim and I worked on this, I remember we worked on him giving as much as he could, because I wasn't going to do any talking. I was going to do the flying. I was going to do outside the window, and he was going to tell me what was going on inside. We were comfortable doing it that way."*
  - The result was concise communication between the crewmembers during the entire landing

- In addition, the LM worked flawlessly, and the coordination between the crew and the ground was also spot on

- In short, Apollo 15 represented a kind of [DE words here…] "plateau of maturity" that integrated all the lessons learned from the first three landings and applied them to making lunar landing, in effect, routine

- The Apollo 15 would end up doing 3 EVAs with the LRV, and returned 77 kg of samples, including the famed "Genesis Rock", which remains one of the most iconic samples returned on Apollo

Fly Me to the Moon
Apollo 16

Fly Me To The Moon – Apollo 16

- LM undocking came at MET 96:13:33 after a largely uneventful pre-undocking prep
  - During the LM prep for undocking, it was discovered that the LM S-band antenna was not rotating around the yaw axis, although it appeared the antenna itself was working OK
    - It was decided that the output bit rate through the Omni antennas, if captured by the Goldstone 210 ft antenna, would be more than adequate to support LM descent and landing
      - However, updates to the LM state vector could not be uploaded automatically as in previous flights, and now had to be sent up verbally and loaded by the LM crew (CDR John Young and LPM Charlie Duke) by hand
  - In addition, there were regulator issues in the LM RCS tanks that indicated there was a leak in the system, requiring fuel transfers to keep tank pressures within limits
    - In the end, RCS System A was deemed sufficiently healthy to conduct the landing

- At MET ≈97:30:00, a significant issue arose during CSM prep for initiating the CSM circularization burn
  - During CSM pre-burn checkout, the SPS Yaw Gimbal Number showed significant oscillation every time it was actuated, vibrating the CSM
  - If not corrected, this would require the LM to redock and bring the CSM-LM stack up to the nominal 60 nm circular orbit, aborting the landing and triggering TEI burn in several hours with the DPS
    - **MET 97:37:35 Mattingly (CM comm):** ”*Okay. Brother, what a way to start the day, huh?”*
    - **MET 97:40:30 Mattingly (CM comm):** ”*…my burn rules say I got to have two sets of servo loops - two on each; got to have all four servo loops to go.”*
    - **MET 97:40:39 Young (LM comm):** ”*I think that's right, Ken.”*
    - **MET 97:40:40 Mattingly (CM comm):** ”*I'm sorry, gang. I don't know what to do with the darn thing. It does it both when the CMC drives it and when we drive it. I've started it, restarted it, and it's just apparently really in the servo loop.”*
  - As per mission rules (see Slide 48), this caused a temporary postponement of Powered Descent Insertion on the first available opportunity while the problem was worked

Fly Me To The Moon – Apollo 16

- At MET 98:11:15, CMP Mattingly began working the problem with the MOCR while both spacecraft initially co-orbited at a separation range of ≈1 nm and then ultimately re-rendezvoused

- After several hours of analysis and simulations, it was decided that the problem did not constitute a structural hazard to the CSM and operation of the SPS was not compromised
  - **MET 102:01:36** CAPCOM Irwin**:** *"Okay, Orion can always tell Casper what his problem is, but it looks like an open circuit in the rate feedback and your servo loop. We've run exhaustive tests down here on the West Coast and East Coast on controllability aspects and structural aspects, and everything looks satisfactory...So we're convinced down here that we have a satisfactory control mode if we have to revert to that one."*

- Subsequently, the LM was given and Go for PDI, which commenced at MET 104:17:26, three orbits and ≈6 hours late
  - The delay cost the crew some hours on the surface, and postponed the first EVA until after a 6-hour sleep period
  - It was realized that, if the original flight plan was followed, the LM crew would have done a 6-8 hr EVA directly after landing, leading to an ≈27 ½ hour long day

Fly Me To The Moon – Apollo 16

- PDI occurred at MET 104:17:28, with nominal engine sequencing and performance
  - The Braking Phase proceeded nominally throughout, with a DLAND/NOUN 69 downrange correction to the trajectory of only 800 ft about 1 min 44 sec into the burn
  - This would be the smallest NOUN 69 correction of any Apollo landing
  - If nothing else, it shows that the extra three orbits managing the CSM problem did not cause significant trajectory dispersion (another problem from Apollo 11 solved…)

- In addition to the low N69 correction, the Altitude/Velocity Lights went out a 50,000 ft, earlier than any other landing, indicating very good performance by the Landing Radar
  - **104:21:02** Duke: “*I say, there's no way to get the Altitude light at this height. (Pause) (Four) minutes... (Pause)*”
  - **104:21:28** Duke: “*We're 50,000 (feet).*”
  - **104:21:30** Young: *“Look at that! Altitude and Velocity lights are out at 50k!”*
  - **104:21:34** Duke: “*Isn't that amazing? Copy that, Houston?*”
  - **104:21:38** Irwin: “*We copy.*”

- Throttle-down occurred at MET 104:24:54, exactly on time

Fly Me To The Moon – Apollo 16

- P63 – P64 transition occurred at MET 104:26:55, with pitchover showing that the LM was targeted for the planned landing site

- During the Approach Phase, the CDR retargeted the LM a number of times to take out dispersions in the spot targeted for landing
  - Young, from the Apollo 16 Mission Report - *"After pitchover, a comparison of the Landing Point Designator with the computer and the movement of the vehicle showed that, if no further trajectory corrections were made, the Lunar Module would land approximately 600 meters north and 400 meters west of the center of the landing ellipse. Therefore, between altitudes of 3000 and 4000 feet, an estimated total of five redesignations to the south were made. The vehicle responded properly."* [ALSJ after MET 104:27:02]
  - Young, from the 1972 Technical Debrief – "*I think the LPD was perfect. I don't have any gripes there whatsoever. When we pitched over, we were north and long and you could see that. I was just letting the LM float in there until I could see where it was going. I took out the north because, according to our pre-flight maps, the north country was a little rougher. There were more (map) contour lines up north and down south; so we took those out and, when we got in close, we backed up a little and put in some rear updates*." [ALSJ after MET 104:27:02]

- The CDR would ultimately make 12 redesignations in P64, although he did not try to put the LM at the exact, pre-planned landing spot
  - Young, from the Apollo 16 Mission Report - *"It was clear that the vehicle was going to be north and west of the pre-mission designated landing spot - 75 meters north of Double Spot Craters. However, there was no major attempt to land at the pre-mission designated spot, nor had there been any intent to do so prior to the flight because the surface traverse capabilities of the Lunar Rover negated the requirement to land precisely at the designated landing spot."* [ALSJ after MET 104:27:20]

Fly Me To The Moon – Apollo 16

- The LM continued in P64 down to <300 ft before the CDR transitioned into P66 with ROD clicks at ≈250 ft
  - Unlike the other Apollo landings, the LMP spent more time looking out the window and giving the CDR specific flight control inputs, specifically information on ROD clicks
    - **MET 104:28:45** Duke: *"Okay, 200 feet, 11 (fps) down. Give me a couple of clicks up."*
      - *Duke - "He's going down too fast. Okay? And our profile calls for 5 foot per second, H-dot; and he's 11. And 12 was our maximum. And, so, I wanted him to slow down a little bit. We were sinking too fast. I wanted to get him closer back to profile." [ALSJ] debrief comment after MET 104:28:25]*

- At MET 104:28:29, a distinct, recognizable LM shadow appears in the direct down-Sun spot, which gave the CDR a superb reference for descent rate and landing spot
  - Young, from the 1972 Technical Debrief - *"At that Sun angle, we could see the rocks (through the dust) all the way to the ground and I think that was a great help. From 200 feet down, I never looked in the cockpit. It was just like flying the LLTV; your reference is to the ground outside. You had another thing that nobody has ever remarked about before, and that was the shadow. I really didn't have any doubt in my mind how far above the ground we were with that shadow coming down (that is, getting closer to them as they approach the surface). I had no scale of reference to the holes; but, with the shadow out there in front of you and coming down, it really takes all of the guesswork out of it. For that kind of Sun angle, if the radar had crumped, I don't think you'd have had a bit of trouble in just going right in and landing just like a helicopter. First, we could see the thing (rocks and other surface features) all the way to the ground; second, the shadow was right there to help you with the rate of descent."*

- At MET 104:29:22, the CDR came to a hover at ≈40 ft, and with lateral rates nulled, settled the LM onto the surface

- At MET 104:29:36, the Contact Light illuminated, the CDR hit the Engine Stop switch and the LM dropped onto the surface at a vertical speed of ≈1.8 ft s^{-1}
  - **104:29:36** Duke: *"Contact! Stop. (Pause while they drop to the surface) Boom."*

Fly Me To The Moon – Apollo 16 Assessment

- Once the CSM SPS gimballing issues got straightened out, the Apollo 16 approach and landing was another well-executed evolution
- Although the crew dynamic was different than on Apollo 15, Young and Duke clearly worked well together, including LMP Duke giving the CDR specifically flight directions so Young could continue to look out the window and assess the landing site
  - Duke, from the 1972 Technical Debrief - *"We'd agreed (pre-flight) that I was going to look out since I had two good craters on my side (Palmetto and Dot).* [ALSJ Comment after MET 104:27:08]"
- As with Apollo 15, Young took the LM down close to the surface (≈250 ft) before he took over and moved the LGC into P66 with ROD clicks
  - According to the debrief comments, he briefly considered letting the LM land itself before having concerns as to the surface roughness at the auto-designated landing spot
  - Young, from the 1972 Technical Debrief - *"It was working so well I was tempted to let it (the PGNS) do the thing all by itself; but the trouble is, we got down low and I could see that we were going to land in that pothole down there."* [ALSJ Debrief Comment: The 'pothole' in question is a shallow, 15-meter crater. John will overfly it and land with his rear foot pad about 3 meters beyond the west rim of the crater.] [ALSJ Comment after MET 104:28:33]
  - Note the following ALSJ exchange as Young got out on EVA-1:
    - **MET 119:04:43** Young: ...Well, we broke the probes off, going straight down. The probes are all standing straight up.
      - *There were probes hanging down from three of the four footpads to trigger the Contact light. Each probe was 68 inches (1.73 meters) long…During the landing, the probes bent as the spacecraft fell the last few feet to the surface; and the probe orientations were a good indication of spacecraft motions during the last seconds of the landing.*
- Apollo 16 was the only "pure highland" site visited on Apollo, and the samples returned were not only unique, they were different from the results expected from pre-mission photogeologic planning
  - The crew's EVA performance, in the face of site geology that was different from the mission plans and shortened EVAs, was superb, and it put their extensive geologic training to work, validating the benefit of detailed geology training
  - One complex breccia ("Big Muehly", the largest rock returned on Apollo at 11.6 kg) is still being carefully dissected and studied

Fly Me to the Moon
Apollo 17

Fly Me To The Moon – Apollo 17

- Apollo 17 was the last mission, but it was one that broke new ground

- First and foremost was the assignment of field geologist Harrison Schmitt as LMP, the first scientist-astronaut to be assigned to a mission
  - Schmitt's assignment caused angst in some circles because he was not a test pilot, although he had in excess of 1,000 hrs flight time in high performance jets
    - Although some of the test pilots felt that his experience was not adequate to fly as an LMP, the belief was not universal
  - Schmitt and CDR Cernan would go on to build a remarkable partnership where Schmitt functioned as an extremely capable LMP to Cernan, while Cernan learned to be a highly capable field assistant for Schmitt while they were executing their EVAs
    - *Cernan - "In thinking about why we worked so well together, the most important point was that we had confidence in each other. Jack is a very astute and dedicated individual, very talented, and I felt very comfortable with him. He was not an aviator and he'll be the first to tell you that. But he took his responsibilities very seriously, learned quickly, and, in terms of technical understanding, was as good as anybody. He wasn't a passenger; he had learned how to be a good co-pilot. In much the same way, I wasn't a geologist, I wasn't a scientist; but I had learned to be a good observer. As soon as we hit the lunar surface, although I was still commander of the crew, Jack was the expert and I was his assistant. We had very different backgrounds....but we both knew enough about all aspects of the missions that we could be confident about working together." [ALSJ Comment after AS-17 MET 113:02:30]*

Fly Me To The Moon – Apollo 17

- An operational issue that was initially raised was that the site chosen for -17 was the Taurus-Littrow valley, a narrow, fault-bounded valley in the mountains on the southeastern edge of Mare Serenitatis
  - The site was chosen because it had a variety of significant geologic features, including potentially young volcanic vents and steep, fault-bounded massifs that shed boulders on to their lower slopes from identifiable rock units on the upper slopes
    - The juxtaposition of these different rock units, combined with the ability to range over the valley with the LRV, had the potential to allow a complete field study of a single locality, as well as returning some of the oldest and they youngest lunar rock units
  - Once the site was chosen, MPAD began working the approach path and the expected landing ellipse and discovered there was an issue with fitting the ellipse into the valley
    - Simply put, the 3-σ cross range component initially the included steep slopes of the North Massif, indicating that there was a low but finite probability that the LM could end up on an approach trajectory into a landing spot that was too rugged, or had slopes that were too steep to land safely
  - However, MPAD determined that scheduling a late state vector update to the LM prior to PDI, which was in turn based on precise landmark tracking by the CSM, allowed landing ellipse to be reduced sufficiently to fit safely into the Taurus-Littrow Valley

Fly Me To The Moon – Apollo 17

- At MET 112:49:56, after a nominal DOI burn, entry into the LM and CSM-LM separation, the crew began the Braking Phase
  - Prior to Apollo 17, CDR Cernan had served as Stafford's LMP on Apollo 10, during which there was an uncontrolled roll and pitch excursion of the LM at staging because of miscommunication in the cockpit on switch settings
  - As a result of this, Cernan decided that, with very few exceptions, the CDR was going to do all the key entries into the LGC on the DSKY and the LMP would do the entries into the AGS on the DEDA

- At MET 112:50:59, the crew was given, and entered a NOUN 69 correction to the descent trajectory of 3,400 ft

- In addition, at about the same time as PDI, the descent fuel quantity light came on, indicating a low propellant quantity
  - Although not an urgent issue at that point, it was a nagging issue for the first two minutes of the Braking Phase
  - At MET 112:51:51, CAPCOM Fullerton suggested the crew cycle the Propellant Quantity Gauging System (PQGS) switch, which fixed the problem (amazing how that approach even works on the LM…)

- At MET 112:52:31, PNGCS and AGS converged and remained in good agreement

Fly Me To The Moon – Apollo 17

- From MET 112:54:15, the Altitude/Velocity lights went out, indicating a good Landing Radar lock on the lunar surface
  - The Delta-H comparison in the LGC looked good, and at MET 112:54:28 the crew did a VERB 57 and accepted radar data into the LGC

- At MET 112:56:07, the LM flew over the rough terrain that was uprange of the landing site, causing the Delta-H calculation to respond to the difference between the calculated "assume a spherical Moon" approach of the LGC with the real terrain data provided by the Landing Radar
  - **MET 112:56:07** Cernan: *"Okay. (Pause) Okay, Houston. As we went over the hump, Delta-H just jumped."*
  - **MET 112:56:16** Fullerton: *"Roger."*
    - *Cernan - "The PGNS was keeping track of our altitude relative to the landing site while the radar, of course, was getting raw data from the terrain below us. Knowing ahead of time that we were going to cross the mountains east of the landing site, we were looking for the altitude difference to change, and it was a comfortable feeling to see it happen." [ALSJ Debrief Comment]*
  - **MET 112:56:18** Cernan: "*And looks like it's back down.*"

Fly Me To The Moon – Apollo 17

- At MET 112:59:18, the LM pitched over and the LMP hit the PRO key to transition the computer into the P64 Approach Phase program
  - **MET 12:59:18** Cernan: “*Pitchover.*”
  - **MET 112:59:19** Schmitt: “*There it is! Proceeded.*”
    - *Cernan - "We still wanted to slow ourselves down by firing forward but now we also had to keep ourselves from falling in too fast toward the surface. I don't know how much we pitched over, maybe from about sixty degrees to about twenty or thirty degrees (actually from 60 degrees to 20); but, when we did, all of a sudden, bam, the lunar surface filled up almost the entire window."*
  - **MET 112:59:21** Cernan: “*And there it is, Houston. There's Camelot (Crater)!*”
  - **MET 112:59:22** Schmitt: “*Wow!*”
  - **MET 112:59:23** Cernan: “*Right on target.*”
  - **MET 112:59:24** Schmitt:” *I see it.*”
  - **MET 112:59:25** Cernan: “*We got them all.*”

Fly Me To The Moon – Apollo 17

- From MET 112:59:26 through MET 113:00:51, the Approach Phase proceeded nominally, with the CDR assessing the approach trajectory and landing spot and the LMP providing the LPD and H/H-dot data
  - **MET 112:59:26** Schmitt: *"42 degrees, 37 degrees through 5500. 38 degrees…"*
  - **MET 112:59:32** Fullerton: *"Challenger, you're Go for landing."*
  - **MET 112:59:34** Schmitt: *"...5000 feet; 42 degrees (LPD angle) through 4000; 47 now; 47 degrees through 3500; 49 degrees. (Pause) 3000 feet; 53 degrees."*
  - **MET 112:59:54** Cernan: *"Okay, I've got Barjea; I've got Poppie; I've got the Triangle."*
  - **MET 112:59:59** Schmitt: *"At 2500 feet, 52 degrees. H-dot is good. At 2000, H-dot is good. Fuel is good. 1500 feet, 54 degrees, Gene. Approaching a thousand (feet). Approaching a thousand feet; 57 degrees. Okay, you're through a thousand, and I'm taking...Radar altitude and PGNS altitudes agree. You're through 800 feet. H-dot's a little high."*
  - **MET 113:00:28** Cernan: *"Okay; I don't need the (LPD angle) numbers any more."*

- Although I can't find any specific citation on the number of ACA redesignations done by the CDR, based on definite roll or pitch changes during the approach, it looks like Cernan redesignated the LM <10 times during the Approach Phase
  - This is also a testimony to the approach trajectory accuracy

Fly Me To The Moon – Apollo 17

- At MET 113:00:51, the CDR switched the LGC into P66 and proceeded into the Landing Phase at ≈300 ft

- From P66 transition to touchdown, the LM did only a bit of maneuvering as the CDR picked the landing spot, and the
  - **MET 113:00:55** Schmitt: *"Okay; 9 feet per second down at 200. Going down at 5. Going down at 5. Going down at 10 (fps); cut the H-dot. The fuel's good. 110 feet. Stand by for some dust. Little forward, Gene."*
  - **MET 113:01:15** Schmitt: *"Moving forward a little. 90 feet. Little forward velocity. 80 feet; going down at 3. Getting a little dust. We're at 60 feet; going down about 2. Very little dust. Very little dust, 40 feet, going down at 3."*
    - *ALSJ Comment: Gene wants about 5 feet per second down for the final phase; 2 feet per second would burn too much fuel and oxidizer. They will land with about 1225 pounds of fuel remaining, enough for about 117 seconds of hovering. For comparison, Neil Armstrong landed with only 50 seconds of fuel/oxidizer remaining… Apollo 11 was the only flight on which less than 100 seconds of fuel/oxidizer remained at touchdown.*
    - *ALSJ Comment: In the landing film, dust becomes easily visible at about 113:01:38; but, by this time, Gene knows exactly where he is going to land. Even in the film, rocks and small craters are visible until the last few seconds. The 16-mm camera is mounted in Jack's window.*
  - **MET 113:01:42** Cernan: *"Stand by for touchdown."*
  - **MET 113:01:43** Schmitt: *"Stand by. 25 feet, down at 2. Fuel's good. 20 feet. Going down at 2. 10 feet. 10 feet."*
  - **MET 113:01:58** Schmitt: *"Contact."*

Fly Me To The Moon – Apollo 17 Assessment

- Apollo 17 proved that a well-trained LMP did not have to be a test pilot, and that putting a trained professional geologist on a lunar crew brought a significant delta in the scientific return from the mission
    - Subsequent use of scientist-astronauts during Skylab, and Mission Specialist in numerous flight roles during Shuttle has proved this point many times over

- In all aspects, the Apollo 17 mission showed the Apollo Program at its best – with the exception of an errant fender on the LRV (fixed by duct tape and landing site approach photos), every system worked flawlessly
    - The LRV, in particular, traversed slopes of 20°+, and drove over 9 km away from the LM to allow the crew to complete all the planned traverses throughout the Taurus-Littrow Valley
    - In addition, the ability of MPAD to reassess standing mission rules to allow the landing ellipse to fit into the valley showed that the Program had reached a stage where previously very conservative boundaries could now be challenged safely, due to the maturity of the hardware, the mission planning and training, and combined astronaut-mission operations team

Conclusions and Implications
for Human Lunar Lander Systems (HLS) Design

Conclusions and Recommendations for HLS – Who's Flying?

- There has been a lot of words written about whether the Apollo crews actually "flew" the LM, but that discussion seems to be largely written by people who are not pilots or don't understand what flying an aircraft means…

- If by "flying", one means that there is a direct mechanical linkage between the pilot and the flight system being actuated, the fact is that with the exception of General Aviation aircraft, *nobody* flies *anything* today
  - Every military jet, from fighter to bomber to helicopter to transport, and every major commercial airliner, has a fly-by-wire system that takes the pilots' inputs on the stick/yoke/cyclic/collective/throttle and passes them through a computer, which then turns those inputs into movements of control surfaces and engine parts

- The fact is that direct control of airplane gizmos (control surfaces, engines, rotors, etc.) is only a small part of the science and art of flying…the largest part is the pilot's moment-to-moment assessment of what's going on with their vehicle, and knowing what to do to complete any flight successfully
  - By that standard, the Apollo crews were flying the LM, even if they never operated the vehicle without the LGC helping out
    - During Powered Descent, their job was to monitor the vehicle and be ready to abort as necessary
    - During the Approach Phase, the LMP was giving guidance data to the CDR, who was looking out of the cockpit and redesignating, as needed, to put the LM in the best spot
    - During the Landing Phase, the CDR was using P66 to maneuver the LM and set it down, with inputs on fuel state, H and H-dot right to touch down
  - Based on my 1,700+ flight hours, I would say this ***is*** flying, in no uncertain terms

- Vehicles landing on any surface need the capability to be flown by pilots, and we should acknowledge that up front and plan for piloted operations with future lunar landers

Conclusions and Recommendations for HLS – System of Systems Design Considerations

- Landers are intrinsically "system-of-system" vehicles, due to the complexity of a landing on an airless body, and the concomitant complexity of the vehicle needed to execute the landing

    - While all the systems in the LM, including the crew, were required to both operate separately *and* in concert with the other systems, it was the crew overseeing and managing any given landing phase that ultimately led to each successful landing

    - ALSJ Comment from Dave Scott: "*I think we - as a group flying the machine, the PGNS, AGS, Irwin, and me, we're all flying that thing - I think we as a collective entity are safer and more efficient if there's a focal point. And I was the focal point. Jim fed things into my ears. The Moon fed things into my eyes, and I could feel the machine operating." [ALSJ, Apollo 15, Comment after MET 104:42:48]*

    - Discussions with Harrison Schmitt have pointed out that human crewmembers represent the best risk reduction system you can put on any future lunar landing vehicle, provided they are properly trained, that they are part of the whole landing vehicle system design, and that the system is designed in such a way that the crew can take over, as they did at some point on every Apollo landing, and fly the vehicle to a safe conclusion of any given landing

Conclusions and Recommendations for HLS – System of Systems Design Considerations

- We *will* need *both* sensor-aided guidance computers to fly the entire landing sequence *and* pilots that can take over at critical points in the approach
  - The vehicle will have to be flown in some phases by a guidance system that is at least as good at the LGC
    - The moment-to-moment flying of the LM, particularly during the Braking Phase, was extremely complex– hence, the need for a highly capable autopilot to manage thrust, vehicle C_g, and state vector calculations
  - However, you also need trained pilots with a good sense of the "moment-to-moment" random perturbations that are present in landing any vehicle on any surface, who are qualified to take over and fly the vehicle in the event that the guidance system fails
    - Every Apollo landing involved the crew taking over and diverting to a different touch down point than was being targeted by the LGC, due to issues with "LM-footpad scale" surface roughness and slope at the original touchdown point
    - *"Given the proper controls and displays, the LM could be "hand flown" throughout the descent, given an effective flight/descent profile."* Dave Scott e-mail to Eppler, 18 January 2020
  - With respect to the use of Heads-Up Displays (a technology not available to Apollo), Dave Scott made this pertinent comment:
    - *"I would much prefer to have Jim read the numbers rather than have anything else (other than the LPD) in the window to scan and interpret -- my job was to find a landing point, total focus on the surface, with no distractions in focus or observation. Heads Up displays are great for some things, but not for landing on the Moon....!!!" (ALSJ, Comment after MET* 102:42:48)
    - *"Good idea <u>if limited</u> to an image that identifies the LGC target point, such as a transparent circle. Otherwise, bad idea. The CDR must be able to focus exclusively on finding a suitable touchdown point – scanning back inside to a screen with numbers and then interpreting the numbers would increase the difficulty and risk significantly. One doesn't close one's eyes when aiming at a target. The transmission of LPD numbers from the LMP to the CDR was very convenient, and it optimized the LMP's inside view and scanning of both the LGC and the instrument panels. This also utilized one of the CDR's important input channels; i.e. ears."* Dave Scott e-mail to Eppler, 18 January 2020

Conclusions and Recommendations for HLS – Astronaut Aviation Experience

- The LM was a two-pilot vehicle, and both the CDR and LMP had critical roles to play and could not have been replaced by the LGC
  - Although some of the LMP function can be replaced with HUDs, etc., the co-pilot function is still very much required (this is why, even with the variety of pilot aids we have at present, there are still 2 pilots required in every airliner)

  - Each future-CDR will need to have a lot of experience flying all kinds of vehicles, both conventional and Short/Vertical Take-Off (S/VTOL), in all kinds of situations – that usually means test pilots
    - One thing that comes out loud and clear in this research is how much that last 1,000' to the lunar surface was about assessing the landing surface and balancing lateral motion, vertical motion and fuel to fly the LM to the best landing spot

  - Future LMPs do not need to be test pilots, but they do need to have a good background in flying, fully experienced with in-flight operations and landing flight hardware
    - Harrison Schmitt did an excellent job as the AS-17 LMP without test pilot experience, but any co-pilot has to be qualified to provide critical flight data (vertical and horizontal velocities, altitudes, fuel state, vehicle status, abort system status) to the Commander, as well as be able to trouble-shoot systems failures while the CDR is flying
      - *"As you know, the LM is a very complex and highly integrated system. For a lunar mission, of particular importance is the communications system, again very complex. The primary function of the LMP is the flight engineer. If e.g. one of the three Earth tracking sites fails, the crew is on their own and any failures will depend on the experience and intuitive skills of the flight engineer (and the pilot). After eight successful Apollo flights, exchanging a geologist for the flight engineer position, especially a highly trained very smart geologist, was a reasonable approach for the final and very mature Apollo mission. As usual, this was risk vs. gain. The issue is: if the flight engineer trained as a geologist fails, lose some science. If the engineer/geologist fails, lose the mission (or die). Therefore, for the first several flights in a vehicle such as the LM, a flight test engineer (or test pilot) maximizes the risk reduction. As to Apollo science, I doubt that A-17 returned more science than A-15 or A-16. Therefore, as a general statement of qualification, I would not conclude that for early flights the LMP functions could be satisfied by a scientist."* Dave Scott e-mail to Eppler, 18 January 2020

  - The only situation that provides the experience needed by both crewmembers is flying real vehicles, in all the random situations that flight vehicles are subject to

Conclusions and Recommendations for HLS – IT Design

- The LM IT assets – the hardware and the software that ran the vehicle during the landing – worked very well together, and without them, we would not have been able to land on the Moon
  - There was an elegance to system that was created because (1) there were very smart folks at Draper, and (2) the same individuals worked on the system from start to finish, so they really cared about what the product, and had an intuitive feel for the hardware and software
  - I think the other part of the reason there was such elegance was because the LGC had no room for junk code that might have unintended consequences in real flight
  - This suggests we need to build this system from scratch
    - I don't think adapting an operating system based on a consumer product is the answer to our software development (i.e., the HLS **should not be** a Windows or iOS driven vehicle!)

- The real crux of this issue is anticipating, preventing and recovering from failures in electronics and IT systems, where failure probabilities are low but consequences are very high
  - <u>All systems fail sometime</u> – it doesn't matter if the system is human or machine
    - The key is to provide paths to graceful recovery, regardless of the hardware fails or the human crew are unable to perform their respective flight duties as Pilot in Command or Co-Pilot
  - Having astronauts involved in the design phase of any future lunar lander will be critical for incorporating flight crew input into both nominal and contingency system design
    - Air France Flight 447 and the 737 Max debacle illustrates what happens when the hardware systems unexpectedly fail and the human operators are unable to take over and recover from that failure
  - The Beresheet and Chandrayan 2 landing failures and the Boeing CST-100 OFT launch failure point out that system errors during dynamic flight phases happen, and may not be recoverable with automated flight systems

Conclusions and Recommendations for HLS - Training Vehicles

(and *nobody* is going to like this one…)

- We will need some kind of flight training vehicle allow CDRs to learn the dynamic, random variations in approach path that will occur for all lunar landings
  - The Lunar Landing Training Vehicle (and its Research Vehicle predecessor) were challenging vehicles to fly (3 of the 5 built crashed, although the pilots successfully ejected in each case), but every CDR that came back from the Moon said that the LLTV trained them better than any other device
    - Dave Scott - *"And, as long as something will keep that vehicle stable...The LLTV landings were manual landings, and the LLTV was a great trainer. I mean, boy, am I glad we had that, because it gave me confidence that I knew what I was doing on the Moon, and I didn't have to think about things. I didn't have to consciously program myself to do things. I was automatic." [ALSJ Comment after MET* 112:59:25]
    - Gene Cernan: *"I think the most significant part of the final phases from 500 feet down, as far as the CDR was concerned, was that it was extremely comfortable flying the bird, either LPDing in P64, and/or flying manually in P66. I contribute that primarily to the LLTV flying operations. That's why the rates of descent and what have you were just very comfortable." [Comment in Apollo 17 Technical Debrief]*
    - Gene Cernan: *"Although there is nothing quite like the real thing, flying the Lunar Landing Training Vehicle (LLTV) had been a step toward realism from "flying" the stationary simulators. In the LLTV you had your butt strapped to a machine that you had to land safely or you didn't make it. It still wasn't landing on the lunar surface, but it gave you a feel for what the actual landing would be like." [ALSJ Comment after MET 112:59:25]*

Conclusions and Recommendations for HLS – Training Approach

- Each Apollo crew had a different personal dynamic, but each LM crew clearly worked extremely well together as a team, and were able to manage the give-and-take associated with flying an extremely complicated machine

  - That speaks to a lot of time training together in the simulators and the classroom as well as time in terrestrial flying machines
    - This was *not* derived from occasional computer-based training exercises – it was lots of hours in the simulator, in the LLTV and in T38s working out the partnership for getting to the Moon
    - Test pilot schools (at least the US Air Force, the US Navy and the British Empire Flight Test School) have a mantra, "Train to Test, Test to Train", which means you train exactly how you would do the same activity for real – Apollo clearly applied that mantra, and it's one we should continue to follow

  - This, in turn, suggests that we need to budget lots of training hours for each integrated Artemis crew
    - The 15 July 1969 Apollo 11 Crew Training Summary indicates that out of 959 hours of training, Neil spent 285 hours, or 30% in the various LM simulators and Buzz did 1017 hours of training, of which 332 hours, 33 %, spent in the LM simulators
    - These figures do not include Neil's LLTV flights nor the 56 hours each of them spent in briefings about LM systems

Conclusions and Recommendations for HLS – Lighting Constraints

- Lighting constraints to landing were a key feature on Apollo, and they ensured that when the LM went into the Approach Phase, the crew could see the terrain they were landing on, and that any obstacles to landing could be seen clearly
  - *"The nature of the lunar surface was the most difficult part of the final descent – there is no scaling to provide a basis of estimating altitude (height). This was the reason the early flights "stair stepped" the final descent. If the size of specific craters could be memorized and interpreted quickly, then they might provide a relative scale for height estimation…"* Dave Scott e-mail to Eppler, 18 January 2020

- These constraints, in turn, drove launch windows, which is why it was possible to launch only once a month

- These kinds of visual constraints have to be factored into site selection and launch window determination for Artemis, particularly on the first landing to any site
  - Regardless of any artificial aids to landing (LIDAR, high-precision landing radar, etc.), the crew has to be able to see what the ground they are landing on looks like, so they can back up the other technology
    - Also note the observation made previously that all systems fail sometime…
  - This will be particularly true for very low Sun angle, very high contrast landing spots on the lunar poles
  - Without this ability, you're just shooting for a spot on the Moon blindly and hoping when the dust settles, your lander is right-side up and the crew can leave again safely – I don't think this is the risk management approach we should apply to Artemis
  - Among other things, even Apollo management wasn't that gutsy, and management today is a lot more risk averse than management was during Apollo

Conclusions and Recommendations for HLS – Landing Site Data

- The lunar surface provides few cues to estimate altitude, descent rate and lateral velocity
  - Craters, at the "final approach scale", are all circular, regardless of size, so the view out the window does not provide good clues to estimating descent rates and time before landing in the last 1,000 ft to the touchdown
    - *Alan Shepard, from the 1971 Technical Debrief - " The elevation and distance estimation of landmarks is always a problem as far as I am concerned. And the only thing I can recommend is that the CDR (Commander) carry in his head the geometry of the landing site, the size of the craters, and the difference between the crater landmarks that are used. He should know exactly what those distances and dimensions are ahead of time. That's one thing you've got to memorize because, as far as I'm concerned, at least, the L&A doesn't give you the feeling of...looking at a crater which is unfamiliar to you and saying that I'm 5000 feet above the ground or 2000 feet above the ground. It's just something that you can't do. You can't relate it to your Earth-bound experience."*

  - Curiously, we grump about lunar regolith (correctly, from a surface ops status), but the horizontal blowing of dust caused by DPS plume impingement was a critical cue that the LM was getting close enough to the surface to land, and the upper sheet of the blowing dust often provided a surface on which to view the LM shadow in the final seconds before landing

  - The more data we have about each site, the better, but until we have prepared landing pads, each landing will be challenge that cannot be met by pre-packaged landing instructions in a guidance computer

Conclusions and Recommendations for HLS - Navigation

- I will paraphrase a line from "The Right Stuff" – the issue isn't landing, the issue is navigation

- The biggest challenge for Artemis will not be the actual act of landing the spacecraft, it will be navigating *to* the spot where we can be reasonably sure that the local topography will not tip the lander over on touchdown
  - LRO data is, at its best (and don't get me wrong, LRO data is fantastic), 0.5 m per pixel, but 1 pixel doesn't tell you much – you need ≈5 pixels to get a reasonable idea of what the topography is, which means your actual knowledge of blocks and holes is around 1-2 meters in size

- This means getting the 3-σ landing ellipse down to where there are NO large, permanently shadowed areas in the ellipse – NONE
  - The Apollo 17 mission almost didn't go to the Taurus-Littrow site because an initial calculation of the 3-σ landing ellipse did not fit into the "landable" portion of the valley
  - It was only through diligent interaction between MPAD, CB and MOD that they were able to work out the procedures that would reduce the ellipse to fit within acceptable topography
  - Again, this was not a photographic issue – by AS-17, we had good panoramic and metric mapping camera data from AS-15 – it was a function of navigation precision during PDI to ensure when the crew pitched over, they would see their nominal landing site

- This means we really have to start working the entire approach methodology now, understanding how a variety of approach ground tracks and landing ellipses map out onto the presumptive south polar landing area
  - As a first step, we can place the Apollo 11 landing ellipse (18.5 km x 4.8 km) over the terrain around Shackleton in real (not averaged) lighting conditions to see how ugly things are
  - We need to make sure that the first Artemis crew will see visible, well-lit, landable terrain in front of them when they pitch over, NOT a black hole!

Sources

Sources

1. Bennet, Floyd V., Mission Planning for Lunar Module Descent and Ascent, NASA Technical Note (Apollo Experience Report) TN D-6846, March 1972.
2. Ennis, W. W. Apollo APS Abort Boundary in LM Descent in Apollo Lunar Landing Missions, Bellcomm Letter Report, B72 02004, 14 February 1972.
3. Eyles, D., Sunburst and Luminary: An Apollo Memoir, Fort Point Press, Boston, 2018, 357 pp.
4. Mindell, D., Digital Apollo: Human and Machine in Spaceflight, MIT Press, Cambridge, MA, 2008, 359 pp.
5. NASA Mission Operations Directorate, Apollo 11 Technical Crew Debrief, 31 July 1969, accessed through the Apollo Lunar Surface Journal, https://www.hq.nasa.gov/alsj/, accessed numerous times between 1 August and 1 December 2019.
6. NASA Mission Operations Directorate, Apollo 12 Technical Crew Debrief, 1 December 1969, accessed through the Apollo Lunar Surface Journal, https://www.hq.nasa.gov/alsj/, accessed numerous times between 1 August and 1 December 2019.
7. NASA Mission Operations Directorate, Apollo 14 Technical Crew Debrief, 17 February 1970, accessed through the Apollo Lunar Surface Journal, https://www.hq.nasa.gov/alsj/, accessed numerous times between 1 August and 1 December 2019.

Sources

8. NASA Mission Operations Directorate, Apollo 15 Technical Crew Debrief, 14 August 1971, accessed through the Apollo Lunar Surface Journal, https://www.hq.nasa.gov/alsj/, accessed numerous times between 1 August and 1 December 2019.
9. NASA Mission Operations Directorate, Apollo 16 Technical Crew Debrief, 5 May 1972, accessed through the Apollo Lunar Surface Journal, https://www.hq.nasa.gov/alsj/, accessed numerous times between 1 August and 1 December 2019.
10. NASA Mission Operations Directorate, Apollo 17 Technical Crew Debrief, 4 January 1973, accessed through the Apollo Lunar Surface Journal, https://www.hq.nasa.gov/alsj/, accessed numerous times between 1 August and 1 December 2019.
11. NASA Manned Spacecraft Center Internal Note 01296, Apollo Mission Techniques, Mission H-2 and Subsequent: Abort from Lunar Powered Descent and Subsequent Rendezvous, 7 January 1970.
12. O'Brien, F., The Apollo Guidance Computer: Architecture and Operation, Springer-Praxis, Chichester, UK, 2010, 439 pp.

Backup Data

LM Descent and Landing Abort Decisions

- Abort Conditions/Responsibilities – General
  - MSC Houston (MCC-H) is responsible for detecting "slow, insidious drift malfunctions" that might contribute to aborts, requiring as much high rate data between the LM and the ground as possible
  - The crew is responsible for detecting errors that require immediate action, largely because comm cycle time for an immediate abort may be as long as 20 seconds

- Overall Abort Decision, Regardless of Abort Mode and Stage of the Lunar Landing
  - Either an Abort or Abort/Stage decision will be made when a malfunction has been detected that precludes a safe descent and landing, or inability to abort later in the landing sequence
  - Abort procedures are designed to finish with the LM in an orbit with a periapsis >30,000' and in a position to rendezvous with the CSM

- Overall abort decision points
  - Propulsion systems
    - Zero or low DPS thrust
      - Includes failure of the DPS to start either automatically after P63 PRO or, if the DPS went into a degraded condition, after attempted CDR manual start using the descent engine command override switch
    - Failure of the DPS to throttle
    - Impending DPS propellant depletion
    - Loss of APS redundant start capability
    - Uncontrollable DPS gimbal failure
  - Guidance and Navigation
    - PGNCS malfunction
    - AGS malfunction prior to High Gate (P63-P64 transition at Pitchover)
    - Lack of Landing Radar (LR) data
    - Incompatible difference between PGNCS and LR data

LM Descent and Landing Abort Decisions

- Overall abort decision points (cont.)
  - Trajectory constraints
    - Violation of specific abort limits seen on MCC-H displays (probably data not available in LM)
  - Landing Site Condition
    - Unsatisfactory for safe landing
    - Redesignation unreasonable given LM trajectory and fuel state
  - General
    - Loss of S-band high rate data or voice communications
    - CSM malfunctions that may affect rescue capability

- Go/No Go for Powered Descent Initiation (PDI)
  - PDI is the first key event in a lunar landing
  - If the LM isn't in a condition to safely land, it is (obviously) better to remain in orbit and either work the condition to a satisfactory conclusion or recover to the CSM
  - For a "Go" decision on PDI, the LM must be able to:
    - Safely land
    - Ascend
    - Rendezvous
    - Re-dock with the CSM
  - A "Go" decision means proceed with the landing sequence start
    - PDI was just the first event in the landing
    - There were more than a few potential events that would trigger an abort between PDI and landing
  - A "No Go" decision means an abort to an orbit that will allow docking with the CSM, or a delay for 1 rev to deal with the problem
  - In addition to appropriate LM system health status (DPS, Ascent Propulsion System (APS), LM ECLSS, appropriate systems for landing), a "Go" for PDI requires

LM Descent and Landing Abort Decisions

- Go/No Go for Powered Descent Initiation (PDI) (cont.)
  - In addition to appropriate LM system health status (DPS, Ascent Propulsion System (APS), LM ECLSS, appropriate systems for landing), a "Go" for PDI requires
    - Agreement between PGNCS and MCC computed target data (uplinked to the crew on Preliminary Advisory Data, or PADs)
      - After AOS on the planned landing orbit (≈PDI -33 mins), MCC-H used tracking data to compute a new LM state vector and to assess orbital perturbations induced during the previous orbit
    - Acceptable alignment of PGNCS
    - Acceptable PGNCS and AGS agreement (AKA PGNCS/AGS residuals)
      - AGS was required through completion of P63 at High Gate; however, depending on the real-time situation and the particular failure mode, a decision would be made to either continue or abort the descent)
    - Adequate high bit-rate and voice comms
    - Proper LM pitch attitude for DPS ignition
    - LGC functioning correctly
    - A verified ullage burn at TIG -7.5 seconds
  - A "No-Go" decision either required an abort burn back up to CSM altitude (≈60 nm) at the nominal PDI time + 12 minutes or a 1-rev delay for assessment and working
    - Decision made between 33 minutes and 6 minutes remaining to ignition of the DPS at PDI (TIG).
  - Ullage maneuver was performed with the RCS just prior to DPS PDI initiation in order to ensure that DPS fuel and oxidizer was properly positioned at the fuel inlet valves.
  - This would have been, in effect, a decision to <u>not</u> land at any time during that mission.

LM Descent and Landing Abort Decisions

- Abort vs. Abort/Stage Decision
  - When the choice is available, DPS-to-orbit (Abort) is used for aborts up to PDI + 5 ½ minutes
  - After PDI + 5 ½ minutes, Abort/Stage is required following DPS fuel depletion or non-recoverable malfunction
  - Abort/Stage decision implies one of the following:
    - DPS fuel depletion following an Abort decision
    - DPS performance limits are violated
    - Excessive RCS plume impingement
    - LM tipover after lunar surface contact

- PGNCS to AGS Switchover Decision
  - PGNCS performance is more critical for the LM when flying the powered descent trajectory than when flying the actual landing
    - This imposed more constraints to continuing the lunar landing in the event of PGNCS degradation during the Powered Descent to Pitchover at High Gate (P63-P64 transition)
  - The abort boundary for poor PGNCS performance was at 30,000' periapsis, requiring a switch to AGS for the subsequent abort (this abort sequence was practiced on Apollo 10)
  - Conditions for the PGNCS abort were:
    - Unacceptable residuals between the ground-based Powered Flight Processor data (PFP) and the lunar orbit-based PGNCS
    - Unacceptable residuals between PGNCS and AGS
    - Unacceptable residuals between the trajectory as established by tracking data from the Manned Spaceflight Network (MSFN) and PGNCS
    - Unacceptable residuals between the trajectory as established by tracking data from the Manned Spaceflight Network (MSFN) and AGS
  - These aborts were all of the "slow insidious drift" type and were called from the ground based on data that was not available in the LM

LM Descent and Landing Abort Decisions

- Post-PDI Abort Decisions for Powered Descent
  - Failure of the DPS to ignite after entry into P63 Braking Phase program and after CDR attempt at manual ignition using the descent engine command override switch
  - PDI initiation starts with a 10% thrust trim phase for 26 seconds, after which the engine goes into a Fixed Throttle Phase (FTP) at 92.5% thrust
    - If DPS fails to go into the FTP phase after the trim phase, the crew will stop thrusting
    - To safely accomplish the landing, PNGCS must be able to control DPS throttle, so manual throttling as the only capability is not acceptable and an abort is called for
  - DPS throttle performance
    - If DPS thrust degrades to <80%, the Thrust/Translation Controller Assembly (TTCA) control switch is cycled from CDR to LMP
    - If this does not recover thrust to ≥92.5% within 100 seconds, an abort/stage decision must be made due to unacceptable DPS nozzle degradation between ≈62.5% and 92.5%, which would cause a catastrophic failure

- LM Attitude and Attitude Rate Monitoring
  - LMP will verify that the control system and Flight Director Attitude Indicator (FDAI) is working by comparing steady state readings of the FDAI error needles on the CDR and LMP FDAIs
    - Unexpected or prolonged errors of 5° sec^{-1} indicates a PGNCS failure
    - Abort on the AGS is subsequently performed

LM Descent and Landing Abort Decisions

- LR Acquisition
  - If the LR good data signal is not received by the PGNCS at H=10,000', landing will be aborted
  - If ground data indicates that the PGNCS performance has exceeded 3σ performance limits, the abort altitude is raised to H=18,000'

- PS Gimbal Drive Actuator (GDA)
  - DPS Gimbal Drive degradation, and subsequent disabling, can be compensated for with increased RCS activity for a wide range of offset errors without violating RCS plume impingement limitations
  - RCS compensation capability increases as a function of the duration of powered descent
  - GDA shutdown will occur any time:
    - DPS engine gimbal trim light is on
    - Attitude errors show offset >±3°
    - Excessive RCS firings

LM Descent and Landing Abort Decisions

- DPS Throttle Performance Limits during Powered Descent (Note: DE Summary of a number of potential abort situations)
  - During the Powered Descent Phase, the LGC was driving the thrust profile, with the requirement of getting the LM to High Gate, within range of the targeted landing site, at an altitude and speed that allowed a safe approach to the landing site
    - Within the DPS limits discussed above, the LGC would command the DPS to provide sufficient delta-v to achieve the landing
    - If (and this is Eppler surmising here…) the DPS performance began to be erratic, the LGC would command the engine appropriately to reach the projected delta-v, horizontal velocity and descent rate constraints for landing
    - However, a serious DPS failure (low or unstable thrust, cyclic variation in commanded thrust) would cause the LM to undergo "large attitude excursions"
  - This resulted in a number of complicated abort scenarios that considered throttle excursions
    - If the DPS throttle performance became erratic prior to ≈80 secs left in P63 (T_{GO}>80), an abort would be recommended
    - If, however, the throttle performance became erratic with T_{GO}<80 secs, the LM could continue to P64 initiation at High Gate

LM Descent and Landing Abort Decisions

- DPS Throttle-Down
  - As noted above, the DPS had issues with continuous operation between 62.5% and 92.5% power; consequently, DPS flew the landing with an initial high, fixed throttle setting until throttle down ≈7 minutes into Powered Descent, at which point it would throttle back to <62.5% for the rest of the landing
    - Throttle down was a critical point in the landing, as inability to throttle down, or throttling down too much, could jeopardize the safety of the crew and successful landing
  - During Powered Descent, MCC-H monitored DPS thrust and made predictions on when throttle down would occur during Powered Descent
    - If throttle down did not occur and DPS would not throttle (indicating a DPS hardware failure), the crew would abort (probably an Abort/Stage)
    - If throttle logic has failed (this is an LGC or engine controller issue), thrust will go to ≈0%, prompting a large LM pitch change at ≈40 secs after throttle down
    - If throttle down has not occurred by the time of P63-P64 program change time (end of Powered Descent and entry into the Approach Phase) +≈15 seconds, the LM will develop radial velocity that prevents landing and the crew would abort

LM Descent and Landing Abort Decisions

- Approach/Visibility Phase (P64 initiation to Landing Phase)
    - If H-dot exceeded the safe limit and didn't return to a safe amount, the crew would abort
    - If the no landing site if available during the limits of H-dot, H and propellant exhaustion limits, the crew will abort
    - After entering P64, MCC-H will monitor which tanks (fuel or oxidizer) have the lowest remaining quantity
        - Based on this assessment, the crew will switch the propellant quantity measurement display to the lower tank for subsequent monitoring
        - However, MCC-H will assume prime responsibility for advising the crew on propellant remaining and will advise the crew at 60 seconds and 30 seconds fuel remaining
        - A "Fuel Depletion "call from MCC-H means that no more than 20 seconds of hover capability or 6 seconds of full thrust remains

- Landing Phase (P66 initiation)
    - Propulsion systems
        - Zero or low DPS thrust
        - Failure of the DPS to maintain acceptable rate of descent through throttle capability
        - Impending DPS propellant depletion
        - Uncontrollable DPS gimbal failure
    - Landing Site Condition
        - Unsatisfactory for safe landing

LM Descent and Landing Abort Decisions

- Post-Landing Phase (P68 program)
    - Immediately after contact, DPS is shut down and the crew monitors LM pitch and roll rates to determine if a tipover is imminent
        - If pitch and roll rates indicate tipover, an automatic Abort/Stage abort is initiated
    - If tipover is not imminent, the crew configures the LM for the T1 and T2 stay decision by finalizing DPS Shutdown configuration and storing the landing point in the AGS in case an abort after T1 or T2 is indicated
    - After a "Go" call for lunar surface stay is made, the crew manually enters Landing Confirmation Program (P68) into the LGC (VERB 37, ENTER, 68, ENTER, PROCEED)