A Brief, Selective History of the Apollo Program

Dean Eppler
Constellation Lunar Surface Systems
Moon 101
10 September 2008
Introduction, and A Few Caveats…

- This lecture is not intended to be a comprehensive history of Apollo
  - First, there isn’t enough time in 1 hour to do a complete history
  - Second, I’m not a historian, and there are more accomplished, qualified scholars out there that could do a better job

- What I want to do is to fill in some of the picture of what happened on Apollo, at least in a technical sense, so folks that were not here (for that matter, were not alive..) when the Apollo crewmembers walked on the Moon can get some sense of what an accomplishment this effort was, and to understand what we learned how to do some 30-40 years ago so we know what the Program accomplished, largely with slide rules, less computer memory than the average modern dishwasher, and just plain guts and initiative…

- Lastly, this is presentation is intended to be “information dense”, long on eye-charts, so folks can go back and read it on the web and get something out of it…
  - No apologies are made, although I promise I won’t read the slides (well, maybe not much…)
"I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish."

John F. Kennedy
Message to the Congress on Urgent National Priorities
25 May 1961
“Let it be clear that I am asking the Congress and the country to accept a firm commitment to a new course of action, a course which will last for many years and carry very heavy costs. If we are to go only half way, or reduce our sights in the face of difficulty, in my judgment it would be better not to go at all.”

John F. Kennedy
Message to the Congress on Urgent National Priorities
25 May 1961
"I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish."

John F. Kennedy
Message to the Congress on Urgent National Priorities
25 May 1961

When John Kennedy made this commitment, this was our sum total manned spaceflight experience: a 1 man, 15 minute-28 second suborbital flight…
“Kennedy’s Apollo was not a spacecraft, not an engineering project, not a means to adding to man’s scientific knowledge. Kennedy’s Apollo was a heap of chips pushed to the center of the table.”

From “Apollo: The Race To The Moon”
Charles Murray and Catherine Bly Cox
So, the question is, how did we go from 15-minute sub-orbital flights to walking on the Moon in less than 9 years?
How We Did It…

- There have been lots of books written on just this subject, but I think (personal bias, here…) the answer has seven components:
  - National will
  - Money
  - Heavy lift launch vehicles
  - Landers
  - Space suits
  - Operations practices
  - Luck

“We shall send to the moon, 240,000 miles away from the control station in Houston, a giant rocket more than 300 feet tall, the length of this football field, made of new metal alloys, some of which have not yet been invented, capable of standing heat and stresses several times more than have ever been experienced, fitted together with a precision better than the finest watch, carrying all the equipment needed for propulsion, guidance, control, communications, food and survival, on an untried mission, to an unknown celestial body, and then return it safely to earth, re-entering the atmosphere at speeds of over 25,000 miles per hour, causing heat about half that of the temperature of the Sun…and do all this, and do it right, and do it first before this decade is out…” John F. Kennedy, speech at Rice University, 12 September 1962
How We Did It…

• National will
  • The Apollo Generation were the folks that won World War II, through a combination of industrial production and solid commitment on the part of the American people; this was a generation that was not only used to succeeding, but understood commitment to a large, long-term goal
    • If the Soviets had not launched Sputnik and Yuri Gagarin into orbit prior to the United States, it’s an interesting speculation to think about whether we would have done Apollo
  • Regardless, the country felt that Apollo was a similar kind of commitment, and it fired the nation up as nothing, short of war, had done before or since
    • One example of the commitment is the, even during the Viet Nam war, draft-age men working on Apollo were deferred from the draft because they were working on a program of national priority

• Money
  • Apollo had financial resources that we can only dream about
    • In 1961, at the time of Kennedy’s commitment, the NASA budget was $964 million, of which Apollo received $100 million*
    • At the peak of Apollo spending in 1966, the NASA budget was $4500 million, with Apollo receiving $2900 million
      • This was something like 4% of the federal budget, compared to the <1% we receive today
    • From “Carrying the Fire”, by Michael Collins, Apollo 11 CMP, “One nice thing about Apollo was that no one ever told us we were running the price up too high.”

How We Did It…

• Heavy Lift
  • The Saturn V remains the largest launch vehicle that has ever been successfully flown
  • The problems that were overcome to create all the stages, all the engines, all the instrumentation, have been the subject of a number of excellent books, most notably “Apollo: The Race To The Moon” by Charles Murray and Catherine Bly Cox
  • Without the Saturn V, it would simply not have been possible to do Apollo by the end of the decade
    • Smaller launch vehicles (e.g., the Saturn 1B) would have meant multiple launches, on-orbit assembly, complex launch window operations, etc.
    • We can do those things now, thanks to our experience building ISS, but they would have been, in my opinion, intractable in the 60s
  • To successfully do the Saturn V, we also had to develop the infrastructure to manage the vehicle, which included the Vehicle Assembly Building, Launch Complex 39, the Crawler and the route out to the pad which has remained a mainstay of manned space since, and will continue to be so for the foreseeable future
How We Did It…

• **Heavy Lift**
  • The Saturn V remains the largest launch vehicle that has ever been successfully flown
  • The problems that were overcome to create all the stages, all the engines, all the instrumentation, have been the subject of a number of excellent books, most notably “Apollo: The Race To The Moon” by Charles Murray and Catherine Bly Cox
  • Without the Saturn V, it would simply not have been possible to do Apollo by the end of the decade
    • Smaller launch vehicles (e.g., the Saturn 1B) would have meant multiple launches, on-orbit assembly, complex launch window operations, etc.
    • We can do those things now, thanks to our experience building ISS, but they would have been, in my opinion, intractable in the 60s
  • To successfully do the Saturn V, we also had to develop the infrastructure to manage the vehicle, which included the Vehicle Assembly Building, Launch Complex 39, the Crawler and the route out to the pad which has remained a mainstay of manned space since, and will continue to be so for the foreseeable future
How We Did It…

• Heavy Lift
  • The Saturn V remains the largest launch vehicle that has ever been successfully flown
  • The problems that were overcome to create all the stages, all the engines, all the instrumentation, have been the subject of a number of excellent books, most notably “Apollo: The Race To The Moon” by Charles Murray and Catherine Bly Cox
  • Without the Saturn V, it would simply not have been possible to do Apollo by the end of the decade
  • Smaller launch vehicles (e.g., the Saturn 1B) would have meant multiple launches, on-orbit assembly, complex launch window operations, etc.
  • We can do those things now, thanks to our experience building ISS, but they would have been, in my opinion, intractable in the 60s

We also had to develop the infrastructure to manage the vehicle, which included the VAB, the pad, the Crawler, and the route out to the pad which has remained a mainstay of manned space since, and will continue to be so for the foreseeable future.
How We Did It…

• Landers
  • The discussion about the decision to go to Lunar-Orbit Rendezvous as the preferred architecture has had a lot of press, as it should - although controversial at the time, it seems clear that alternate approaches would have taken longer to develop, cost more, taken more launches, etc.
    • In particular, some of the early views of going to the Moon (particularly those seen in the early articles about going to the Moon, such as were in Colliers magazine in the 1940s) would have landed very large vehicles (Saturn V size) on the lunar surface
  • In any event, the decision to go LOR was the start of the fun, NOT the end…now, someone had to build the lander
  • The Lunar Module (LM) was the first “true” spacecraft, being only able to operate in a vacuum, with no TPS to allow it to successfully reenter the Earth’s atmosphere
  • Grumman built into the LM a substantial margin, more than was probably justified for a simple “flags and footprints” mission
    • As the Program matured, the LM’s payload went from carrying a minimal science package on Apollo 11 to carrying a larger, significantly larger payload by the late missions, to include more advanced science packages, a rover, consumables for 3 days of lunar operations and even a telescope
How We Did It…

- **EVA Systems**
  - During Gemini IX in June, 1966, Gene Cernan did an EVA in a pressure garment that left him winded, beat up, and with a visor so fogged that he had to use his nose to wipe a spot to see through to get back to the hatch of the spacecraft after failing to complete the main objectives of the EVA
    - Once back to his seat, the suit was so immobile that gaining reentry to the spacecraft and closing the hatch was excruciating and potentially life-threatening*
  - In December, 1972, Cernan again went EVA
    - This time it was for three successive EVAs over three days on the lunar surface, compiling over 21 hours of solid field geology on the lunar surface with nary a qualm
  - In less than 3 years, the EVA system technology improved to the point where the EVAs on Apollo were routine
    - This success was a combination of hard work, good engineering, and a lot of experimentation
    - By the time Apollo was finished, NASA had built over a dozen different suits, experimenting with different degrees of mobility, different operating pressures, and different approaches to thermal management for the crewmember†
    - In addition, a Portable Life Support System (PLSS) was developed that was easily carried in lunar gravity, and performed over 25 EVAs without a single major malfunction

*See “The Last Man On The Moon”, by Eugene Cernan and Don Davis
†See “U.S. Spacesuits”, by Kenneth S. Thomas and Harold J. McMann
How We Did It…

• Operations Practices
  • A host of legendary individuals (we all know their names…) invented the operations practices that enabled us to go to the Moon, practices that we are still using today
  • In addition to developing and staffing the flight control teams, Apollo also developed the training approaches and the flight dynamics techniques that were not only successful on Apollo 11, but which evolved over the course of the program to allow us to do the extensive exploration conducted on the last three missions
  • One example is the evolution of LM descent operations
    • On Apollo 11 and 12, the LM engine was used to initiate an orbital altitude change from the pre-landing circular orbit of ≈100 km down to ≈15 km (called Descent Orbit Insertion, or DOI), where powered descent to the lunar surface would be initiated
    • On Apollos 14-17, the Command/Service Module initiated the pre-landing descent orbit, which left extra fuel in the LM descent stage to initiate the landing
    • The extra margin this fuel gave the LM was what was used to add on rovers, more science payloads, and consumables for 3 days on the lunar surface
  • This operational flexibility, combined with robust vehicle design, was the key to getting the Apollo 13 crew home
OK, so now, what exactly DID we do on the Moon…?
The Apollo Program landed six missions on the lunar surface after a preparatory series of missions to Earth orbit and lunar orbit:

- Apollo 1 - first planned mission lost when a fire swept through the spacecraft and killed the prime crew
- Apollo 2-6 - unmanned flights testing various pieces of Apollo hardware
- Apollo 7 - low Earth orbit (LEO), check of Command/Service Module (CSM) system
- Apollo 8 - first lunar orbital mission; undertaken when the LM was behind schedule
- Apollo 9 - checkout of CSM/LM stack in low Earth orbit
- Apollo 10 - “dress rehearsal” for landing; CSM/LM stack testing in lunar orbit, including descent orbit insertion and rendezvous in lunar orbit

All the landing sites were on the front side, largely in the equatorial region.
The Apollo Crewmembers

- Apollo 1
  - CDR - Gus Grissom
  - CMP - Ed White
  - LMP - Roger Chaffee

- Apollo 7
  - CDR - Wally Schirra
  - CMP - Walt Cunningham
  - LMP - Don Eisele

- Apollo 8
  - CDR - Frank Borman
  - CMP - Jim Lovell
  - LMP - Ed Anders

- Apollo 9
  - CDR - Jim McDivitt
  - CMP - Dave Scott
  - LMP - Rusty Schweikart

- Apollo 10
  - CDR - Tom Stafford
  - CMP - John Young
  - LMP - Gene Cernan

- Apollo 11
  - CDR - Neil Armstrong
  - CMP - Mike Collins
  - LMP - Buzz Aldrin

- Apollo 12
  - CDR - Pete Conrad
  - CMP - Dick Gordon
  - LMP - Alan Bean

- Apollo 13
  - CDR - Jim Lovell
  - CMP - Jack Swigert
  - LMP - Fred Haise

- Apollo 14
  - CDR - Al Shepard
  - CMP - Stu Roosa
  - LMP - Ed Mitchell

- Apollo 15
  - CDR - Dave Scott
  - CMP - Jim Irwin
  - LMP - Al Worden

- Apollo 16
  - CDR - John Young
  - CMP - Ken Mattingly
  - LMP - Charlie Duke

- Apollo 17
  - CDR - Gene Cernan
  - CMP - Ron Evans
  - LMP - Harrison Schmitt

Apollo 15 Crew, geologic training trip, Rio Grande Gorge, NM
Apollo 11

- Apollo 11 was, in a sense, the final engineering mission that followed in the wake of Apollos 7-10
  - Each of these previous missions proved out the system progressively one layer at a time as we went from LEO with the CSM (Apollo 7), to lunar orbit with the CSM (Apollo 8), to LEO with both the LM and CSM (Apollo 9), to lunar orbit with the CSM/LM stack in a simulated landing (Apollo 10)
  - It’s mission was to fulfill Kennedy’s commitment - land men on the Moon and return them safely to the Earth
  - In addition, it had the objective to prove out the EVA system, and to return, if possible, the first science from the lunar surface, in the form of a small set of deployed science instruments, and a modest collection of lunar samples

<table>
<thead>
<tr>
<th>Apollo 11 Surface Operations Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Date</td>
</tr>
<tr>
<td>Landing Site</td>
</tr>
<tr>
<td>Targeted Landing Latitude</td>
</tr>
<tr>
<td>Actual Landing Latitude</td>
</tr>
<tr>
<td>Targeted Landing Longitude</td>
</tr>
<tr>
<td>Actual Landing Longitude</td>
</tr>
<tr>
<td>LM Distance to Target Landing Ellipse</td>
</tr>
<tr>
<td>PDI Burn Duration</td>
</tr>
<tr>
<td>Hover Time Remaining at Shutdown</td>
</tr>
<tr>
<td>Time on the surface</td>
</tr>
<tr>
<td>Number of EVAs</td>
</tr>
<tr>
<td>Total EVA time</td>
</tr>
</tbody>
</table>
Apollo 11

- The Apollo 11 landing was a cliff-hanger, even beyond the fact that it was the first lunar landing
  - Problem 1 - The computer saturated during the final approach phase of the descent, causing it to send C&W alarms which were, ultimately, not serious, but gave everyone (with the possible exception of Draper Labs and Steve Bales) a cardiac arrest
    - Luckily, good training with extensive JISs led to the discovery of the possibility of these alarms prior to the flight, so the crew and FCR team essentially ignored them and continued the approach
  - Problem 2 - A combination of navigational errors led to the vehicle being targeted “long” with respect to the preplanned targeting ellipse
    - From the MSC 00171, Apollo 11 Mission Report: “The onboard state-vector errors at powered descent initiation resulted from a combination of the following: a) Uncoupled thruster firings during the docked landmark tracking exercise; b) Unaccounted for velocity accrued during undocking and subsequent inspection and station-keeping activity; c) Descent orbit insertion residual; d) Propagated errors in the lunar potential function; e) Lunar module venting.”
  - Problem 3 - As they approached the designated landing point, it was clear that the LM was headed into a boulder field that surrounded a relatively young crater
    - From Apollo 11 crew debrief: “ARMSTRONG: As we approached the 1500-foot point…we [could see] were landing just short 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….it became obvious that I could not stop short enough to find a safe landing area. I then proceeded to look for a satisfactory landing area and the one chosen was a relatively smooth area between some craters and a ray-type boulder field.”
  - Problem 4 - As about 30 m, the ground began to be obscured with blowing material
    - From Apollo 11 crew debrief: “ARMSTRONG: It was a little bit like landing an airplane when there’s a real thin layer of ground fog, and you can see things through the fog. However, all this fog was moving at a great rate which was a little bit confusing.”
Apollo 11 Results and Lessons Learned

• Apollo 11, in spite of it’s relatively short duration (8 days) and short lunar stay time, taught us lessons that we would apply for the rest of the Apollo program
  • Due to a combination of navigational and procedural errors, LM landed long, and almost landed in unacceptable terrain
    • Due to both pilots’ actions, the vehicle was flown downrange and landed successfully; if it had been a purely automated landing, the LM would have either had to abort, or would have crashed
    • It emphasized the requirement to absolutely understand the LM position at PDI, and to absolutely control spurious delta-v inputs to the LM between final position hack and that start of PDI
  • The lunar surface was covered with loose, ground-up rock that was very compacted below about 10 cm, but loose and fluffy from the surface down to 10 cm
    • This material would be both a bane and a boon - operational a pain in the neck, but providing a record of lunar and solar history that we are still unraveling
  • While the crew was collecting samples, Neil Armstrong recognized that there would be empty space in the rock box, and filled up those spaces with scooped up soil
    • This became soil sample 10005, one of the most comprehensive soil samples collected on the lunar surface which yielded the first pieces of highland rocks and let ultimately to people developing the “Magma Ocean hypothesis”
  • Largely on Neil Armstrong’s initiative, the crew walked about 100 m east of the landing point to the edge of Little West Crater, which provided the first photographic evidence of both the lunar bedrock, and the depth of the regolith layer
Apollo 12

• Apollo 12 was the first step toward doing real science on the Moon, but in many ways, it was still an engineering test flight
  • Having landed safely on Apollo 11, it was realized that the next step was to prove that we could land anywhere, carry out extended exploration operations, and deploy long-term science monitoring payloads that could return data for a number of years
• In order to build on Apollo 11, it was decided that the Apollo 12 mission would attempt to land on a different mare surface within walking distance of the Surveyor III spacecraft, which soft landed on the Moon in April of 1967
  • In addition, the crew would deploy the first Apollo Lunar Scientific Experiments Package (ALSEP), an array of science monitoring instruments with a lifetime of at least 3 years

<table>
<thead>
<tr>
<th>Apollo 12 Surface Operations Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Date</td>
</tr>
<tr>
<td>Landing Site</td>
</tr>
<tr>
<td>Targeted Landing Latitude</td>
</tr>
<tr>
<td>Actual Landing Latitude</td>
</tr>
<tr>
<td>Targeted Landing Longitude</td>
</tr>
<tr>
<td>Actual Landing Longitude</td>
</tr>
<tr>
<td>LM Distance to Target Landing Ellipse</td>
</tr>
<tr>
<td>PDI Burn Duration</td>
</tr>
<tr>
<td>Hover Time Remaining at Shutdown</td>
</tr>
<tr>
<td>Time on the surface</td>
</tr>
<tr>
<td>Number of EVAs</td>
</tr>
<tr>
<td>Total EVA time</td>
</tr>
</tbody>
</table>
Apollo 12 - Results

• Precision landing is possible (in this case, to within <10 m of the planned landing spot), making it clear that other, more ambitious science missions to more challenging terrain is possible
• The Surveyor III was, in fact, our first LDEF mission, and it showed a number of things
  • Hardware survives reasonably well on the lunar surface for extended periods of time
  • The Surveyor III received a shower of dust from the LM engine as it passed by, but otherwise, there was no evidence of significant lateral transport of material on the lunar surface through natural processes
• The ALSEP packages proved their worth, although their deployment was a time consuming effort that took up 1 EVA
• Walking traverses in excess of 2 km can be accomplished
• Operations in low sun angles (<10°) can be difficult and disorienting
• In addition to collecting a substantial suite of rocks (which turned out to be substantially different from the Apollo 11 samples), the crew observed a number of mound-like features on the lunar surface that were unexpected
  • Surface time did not, however, allow the crew to do more than photograph and describe them
Apollo 14

- Apollo 14 was the first mission that went to a physically challenging (i.e., not flat mare) site that had substantive science interest
- In addition to the ALSEP, the crew had a pull cart called the Modularized Equipment Transporter (dubbed “Shepard’s Rickshaw) that they would take along on what was to become the most physically challenging EVA that was completed on Apollo
  - Cone Crater was a young 340 meter crater that punched through, and excavated, a rock unit dubbed the Fra Mauro Formation, which was believed to be ejecta from the Imbrium Basin event
  - The site was also overlain by material that appeared to be in the ray pattern of Copernicus Crater, a young, 98 km wide crater that is a typical young, rayed crater

<table>
<thead>
<tr>
<th>Apollo 14 Surface Operations Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landing Date</strong></td>
</tr>
<tr>
<td><strong>Landing Site</strong></td>
</tr>
<tr>
<td><strong>Targeted Landing Latitude</strong></td>
</tr>
<tr>
<td><strong>Actual Landing Latitude</strong></td>
</tr>
<tr>
<td><strong>Targeted Landing Longitude</strong></td>
</tr>
<tr>
<td><strong>Actual Landing Longitude</strong></td>
</tr>
<tr>
<td><strong>LM Distance to Target Landing Ellipse</strong></td>
</tr>
<tr>
<td><strong>PDI Burn Duration</strong></td>
</tr>
<tr>
<td><strong>Hover Time Remaining at Shutdown</strong></td>
</tr>
<tr>
<td><strong>Time on the surface</strong></td>
</tr>
<tr>
<td><strong>Number of EVAs</strong></td>
</tr>
<tr>
<td><strong>Total EVA time</strong></td>
</tr>
</tbody>
</table>
Apollo 14 - Results

- Apollo 14 experienced a number of serious challenges that compromised science return badly
- The most serious of these was dealing with the terrain
  - First, it was hilly, steep (up to $\approx 15^\circ$) and covered with regolith that made footing difficult, and made pulling the MET essentially impossible
  - Second, the nature of the topography (endless rolling hills) made navigation very difficult - the crew misjudged distances, crater sizes, and position to the point that they not only did not make it to the rim of Cone Crater, they walked right past the rim and didn’t know it until after the mission was over
  - This has significant implications for walking traverses in non-mare terrain; particularly, without a navigation system (i.e., an LGPS), a crewmember on a walking traverse could become lost right in their own backyard
- The MET proved to be a pain to work with, and on the steeper, rocky slopes, the wheels would not roll
  - This caused the crew to have to pick it up and carry it (this must have been like running a three-legged race while carrying a shopping cart)
- The ALSEP array generally worked well, but a number of items, particularly the thumper for the geophone array, worked only intermittently, causing the LMP to have to re-do much of the geophone run
The J-Missions - Apollo 15, 16 and 17

• The successes of the first three missions set the stage to undertake more challenging landing sites that would emphasize scientific exploration over engineering tests
  • The experience at progressively more topographically rough sites from Apollo 11 to 14 gave us confidence that we could go into the mountains on the Moon where the good geology is
  • The record of increasingly precision landings validated our landing philosophy and our navigational capability
  • Experience with the Command/Service Module gave us confidence with the vehicle propellant margins, allowing us to shift the DOI burn to the CSM, freeing up LM descent engine fuel, which in turn allowed us the add cargo to the LM
  • The experience on Apollo 14 taught us that walking traverses in terrain other than maria was a difficult and inefficient method of travel
• Apollos 15-17 went to the Moon equipped with enough consumables for a 3 day stay, the Lunar Roving Vehicle (LRV or simply, the Rover) and improved pressure garments that had enhanced mobility (among other things, they allowed one to sit down on the Rover)
• There was also an expansion in mission rules to take advantage of these capabilities
  • We had lots of discussions about walkback and the rules that we came up with were generally compromises. If some of the real conservative people had had their way, we wouldn't have gone more than a mile from the LM; but we finally decided that we wouldn't consider a worst-case worst case of both the Rover and one of the PLSSs failing. Otherwise, there wouldn't have been much point in taking the Rover...You don't want to take unnecessary risks; but the Rover had four drive motors and two sets of batteries and the chance of both the Rover and one of the PLSSs failing was pretty small." Eugene Cernan, Apollo 17 CDR, Apollo Lunar Surface Journal interview
Apollo 15 landed on a mare surface between the Apennine Mountains and along the edge of Hadley Rille:

- The mission objectives were to explore both the rille to the east and the massifs to the south of the landing site, sampling the highland rocks in-situ to determine the composition of what was hoped to be primordial lunar crust, and to sample and photograph the rille both to collect samples from a new mare site and to provide some insight into the origin of lunar rilles.
- All prior samples of the putative ancient lunar crust had come from soil samples.

- In addition, an enhanced ALSEP array included a heat flow experiment, which would require drilling several 3 m holes in the regolith, which would give the deepest core sample of the regolith planned on Apollo.

### Apollo 15 Surface Operations Statistics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Date</td>
<td>30 July 1971</td>
</tr>
<tr>
<td>Landing Site</td>
<td>Hadley Apennine region</td>
</tr>
<tr>
<td>Targeted Landing Latitude</td>
<td>28.0816° North</td>
</tr>
<tr>
<td>Actual Landing Latitude</td>
<td>26.1322° North</td>
</tr>
<tr>
<td>Targeted Landing Longitude</td>
<td>3.6853° East</td>
</tr>
<tr>
<td>Actual Landing Longitude</td>
<td>3.63386° East</td>
</tr>
<tr>
<td>LM Distance to Target Landing Ellipse</td>
<td>549 m Northwest</td>
</tr>
<tr>
<td>PDI Burn Duration</td>
<td>739 sec</td>
</tr>
<tr>
<td>Hover Time Remaining at Shutdown</td>
<td>103 sec</td>
</tr>
<tr>
<td>Time on the surface</td>
<td>66h, 55m</td>
</tr>
<tr>
<td>Number of EVAs</td>
<td>3</td>
</tr>
<tr>
<td>Total EVA time</td>
<td>18h, 35m</td>
</tr>
</tbody>
</table>
Apollo 15 - Results

• Apollo 15 was a tremendously successful mission
  • The crew was able to range throughout the area, returning one of the most pristine samples of the lunar crust found on Apollo (15415, the Genesis Rock), and collecting the only photo-documentation of lunar stratigraphy in the wall of the rille we recovered on Apollo
  • The LRV proved its worth, taking the crew up slopes in excess of 20° and distances well in excess of the 2 km achieved with walking on Apollos 12 and 14
    • Some slopes were so steep that the crew had to secure the rover in a small crater to keep it from sliding back down the slope
• The mission was not without its difficulties however, but the crew showed exception initiative in overcoming those problems
  • LRV steering had some issues - in particular, the rear steering failed, but the crew was able to navigate well in all terrains
  • LRV fenders proved fairly fragile and at least one failed, resulting in the crew getting showered in dust while driving
  • The drill proved highly problematic, particularly in extracting the core
    • The effort proved so difficult is was not achievable in the time allotted, requiring canceling of about half of EVA 3 and resulting in not visiting the North Complex
    • In addition, the effort seriously damaged Dave Scott’s fingers and caused Jim Irwin some cardiac irregularities that were later diagnosed as a minor heart attack
  • The timeline and ground “supervision” proved, at times, problematic in light of what the crew were seeing in the field
    • At one point, the crew invented a seat belt problem in order to sneak off and get a sample of a rock (later called “The Seatbelt Basalt”) not on the EVA plan
    • At other times, the crew ended up doing geologically inappropriate activities at certain locations when other actions were called for (e.g., collecting a rake sample when a rock sample would have been more useful)
Apollo 16 landed in the Descartes region of the central nearside highlands; it was the only “pure” highlands site visited on Apollo
   - The mission objective was to conduct geologic observations on a number of highland landforms that were thought to represent highland volcanism, as well as set up the fourth ALSEP array
   - The mission was notable for a number of reasons
     - Poor photography on previous missions meant we had limited understanding of the landing site topography; from pitchover down to the surface, it was a pure flying job
     - The site geology turned out to be different from what the crew had been led to expect, but the quality of their geologic training allowed them to recover and do exceptional, original field work

---

**Apollo 16 Surface Operations Statistics**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Date</td>
<td>20 April 1972</td>
</tr>
<tr>
<td>Landing Site</td>
<td>Descartes region</td>
</tr>
<tr>
<td>Targeted Landing Latitude</td>
<td>9.0002° South</td>
</tr>
<tr>
<td>Actual Landing Latitude</td>
<td>8.97301° South</td>
</tr>
<tr>
<td>Targeted Landing Longitude</td>
<td>15.5164° East</td>
</tr>
<tr>
<td>Actual Landing Longitude</td>
<td>15.50019° East</td>
</tr>
<tr>
<td>LM Distance to Target Landing Ellipse</td>
<td>57 m Northwest</td>
</tr>
<tr>
<td>PDI Burn Duration</td>
<td>734 sec</td>
</tr>
<tr>
<td>Hover Time Remaining at Shutdown</td>
<td>102 sec</td>
</tr>
<tr>
<td>Time on the surface</td>
<td>71h, 2m</td>
</tr>
<tr>
<td>Number of EVAs</td>
<td>3</td>
</tr>
<tr>
<td>Total EVA time</td>
<td>20h, 14m</td>
</tr>
</tbody>
</table>
Apollo 16 - Results

• Apollo 16 was another extremely successful mission
  • In the truest tradition of science, it showed that the best reasoning can lead to the wrong conclusions, at which point, good scientists (in this case, John Young and Charlie Duke) adjusted and moved forward
  • The samples indicated that the highlands were extremely messy geologically, dominated by impact and showing no evidence of recognizable volcanic events
• The mission also showed the value of detailed, extensive, geologic training for crewmembers, as well as having crewmembers with initiative and good observational powers
  • If the crew had not had >1000 hours of geologic training, it’s unlikely the science return would have been as good
• Although the highlands turned out to be not as nasty a place to land in and drive about, young impact craters proved to have surrounding boulder fields that were very rocky and not trafficable with the LRV, and interiors that were steeper than expected
• There were, however, some downsides to the mission
  • The heat flow probe cable, which John Young had identified as a potential entanglement hazard in pre-mission exercises, was pulled out of the instrument during emplacement
  • Although a method of repair was worked out on the ground, it would have led to a significant loss of one EVA, which was determined to be unacceptable
  • Difficulties with the CSM resulted in a landing that was late by 2 orbits
    • This, in turn, led to truncation of the third EVA
    • The science backroom had to engage in a drastic replanning effort, which ultimately showed the resilience of the system to be able to do real-time replanning
Apollo 17

- Apollo 17 landed in the Taurus Littrow valley, a mare surface that extends eastward from Mare Serenitatis between two massifs that were expected to have uplifted pre-Serenitatis lunar crust.
- The mission was noteworthy for including the first geologist to fly in space, and it made for a different crew dynamic.
  - During the landing, Harrison Schmitt was clearly Eugene Cernan’s co-pilot, but once out on the surface, Schmitt took the fore as the lead scientist with Cernan backing him up.
- The mission was also noteworthy in that the crew traveled farthest from the LM (9.2 km) and drove up the steepest slopes ($\approx 26^\circ$) of any Apollo mission.

<table>
<thead>
<tr>
<th>Apollo 17 Surface Operations Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing Date</td>
</tr>
<tr>
<td>Landing Site</td>
</tr>
<tr>
<td>Targeted Landing Latitude</td>
</tr>
<tr>
<td>Actual Landing Latitude</td>
</tr>
<tr>
<td>Targeted Landing Longitude</td>
</tr>
<tr>
<td>Actual Landing Longitude</td>
</tr>
<tr>
<td>LM Distance to Target Landing Ellipse</td>
</tr>
<tr>
<td>PDI Burn Duration</td>
</tr>
<tr>
<td>Hover Time Remaining at Shutdown</td>
</tr>
<tr>
<td>Time on the surface</td>
</tr>
<tr>
<td>Number of EVAs</td>
</tr>
<tr>
<td>Total EVA time</td>
</tr>
</tbody>
</table>
Apollo 17 - Results

• Apollo 17 had probably the best science return of any Apollo mission
  • The presence of a geologist on the crew, coupled with a test pilot who also had impressive observational skills and good geologic training, led to a very high quality of basic geologic observations in the field
  • The landing site also “cooperated”, providing not only the best access to rocks that could be tied, through boulder tracks, to bedrock units, but also with an unprecedented surprise find of orange soil at Station 4, Shorty Crater
  • Lastly, some new geologic tools, such as the LRV soil sampler (nicknamed the pooper scooper) made it possible to take quick grab samples in many locations without cutting into the timeline
• There were some operational glitches that made the mission interesting, however
  • As on Apollo 15, the LRV fender failed, which necessitated a improvised fix with tracking maps and camera clamps
  • In some cases, the interest in a particular site led to going over the planned timeline, causing restricted time at successive sites
    • This got particularly exciting when “going over” at the South Massif sites led to restricted time when the discovery was made at Shorty Crater
Why Apollo Matters...What We Learned

- The Moon is not simply a dust ball collected up from the remnants of solar system formation; it is a geologically complex body that has had a long and complicated history associated with the formation and several billion years of the solar system. Further, we had the realization that the Earth went through the same history, which was unimaginably more violent than we had ever considered prior to Apollo.

- Prior to Apollo, most scientists thought the Moon had a composition similar to a large meteorite, and that it was a simple body composed of accumulated debris that was swirling around at the beginning of the Solar System. It was not assumed to have any geologic processes, although there was much controversy about whether lunar craters were formed by volcanic or impact processes. In short, the assumption was that this body was accumulated under generally quiescent processes about 4.5 billion years ago, after which nothing happened except the occasional explosion on its surface. Apollo showed us that the formation of the Moon and, by inference, the Earth, was extremely violent, involving the creation of huge impact basins (1000s of km across), the melting of the entire planet (!) to a depth of several hundred kilometers, and the eruption of significant volumes of lava. As we have sent spacecraft throughout the Solar System since Apollo, we have learned that the story of the Moon is the story of the Solar System, but the place we first learned that lesson was on the Moon, with discoveries that came from the Apollo Program.
Why Apollo Matters...What We Learned

- How to build robust spacecraft that could successfully complete both a nominal and contingency mission and bring the crews home safely

  - The Apollo spacecraft, from the boosters that launched them to the Command-Service Modules and Lunar Modules, were simply marvels of engineering, with few single-point failures and dead ends as far as crew survival and mission accomplishment. Apollo 13 has been correctly described as a successful failure, particularly in that the scenario that developed had never been practiced and had only been considered in passing as a way-out-of-the-box possibility. Some other accomplishments that are not often appreciated include Apollo 12 landing within 13 meters of its designated landing site, and the ability of the LM to accommodate an increase in lunar surface time from <1 day (22 hours on the surface for Apollo 11) to >3 days (75 hours on the surface for Apollo 17) as well as add on a rover and the necessary consumables to allow the Apollo 15, -16 and -17 crews to do three 7-8 hour EVAs.
Why Apollo Matters...What We Learned

• How to do mission operations from the surface of the Earth to the surface of the Moon, a discipline that simply didn’t exist prior to the beginning of Mercury-Gemini Apollo and without which nothing on Apollo could have been accomplished.

• Simply put, we didn’t know how to do this in 1959; guys like Chris Kraft and Gene Kranz invented the whole process of mission operations, to paraphrase Indiana Jones, making it up as they went. It was a combination of engineering experience, military operations experience and wisdom beyond their years that came up with the whole profession, and it shone on all the missions, but particularly on Apollo 11 and Apollo 13.
• How to build very large boosters, culminating in the Saturn V, which could deliver to orbit an equivalent mass of the entire loaded Atlas and Mercury spacecraft that we’d been using to do our first manned missions only 6 years earlier.

• When Kennedy set the goal of going to the Moon, we didn’t have the Saturn V; it was on the drawing board, but it was mostly a gleam in the Huntsville guys’ eyes. Six years later, we launched the first Saturn V and it lifted an equivalent mass to what we had sitting on the pad for most of the Mercury flights into orbit. If you read the Apollo 8 launch transcript on the Apollo Flight Journal transcript for Apollo 8, for instance, you can see what an elegant piece of engineering the Saturn V was (http://history.nasa.gov/ap08fj/); we will be doing well if we can emulate half the elegance in our future vehicles.
Why Apollo Matters...What We Learned

• How to do planetary surface scientific exploration, from pressure garments that would allow mobility across the surface to do geologic exploration, to portable life support systems that would keep crewmembers alive for up to eight hours on the lunar surface and in space, to rovers that could reliably transport the crew significant distances (up to 9.2 km on Apollo 17) without significant exertion and use of the crew’s oxygen and cooling water, to the orbital science packages that allowed us to photograph and remotely sense lunar composition, to scientific instrument packages that could be installed on the surface, reliably run for years and provide critical time-phased information on the lunar environment.

• This was nothing short of miraculous – Apollo started out primarily as a flags and footprints kind of program, with little commitment to doing anything beyond John Kennedy’s vision. If you look at how far we progressed in what each mission got done, with a total time between the first landing and the sixth (July 1969 to December 1972), it’s amazing. There is a sense abroad in some scientific communities, all ignorant and arrogant, that little science was produced from Apollo; nothing could be further from the truth. As I alluded to above, EVERYTHING we know now about the history of the Solar System is informed by what we saw on the lunar surface, correlated with the samples that the crews returned. That we were able to do this ties directly back to the surface systems that were produced that allowed the crew to do the productive exploration work on the lunar surface, and provided data on the state of the Moon after they left.
Apollo Lessons for Constellation

- Planetary geologic exploration is not just a function of time, it’s a function of observing, testing hypotheses and revisiting locations if it seems appropriate to better understand field relations
  - This includes how to sample...what, how big, how small, how to handle the samples
  - This also includes ground control vs. decisions made on the planet’s surface, something that will be vital not only when we go back to the Moon, but for Mars as well
- Things break, despite your best designs and plans
  - Plan for it, both in terms of time, repair capability and crew selection and training
  - If a crewmember or hardware tester finds something that needs fixing, don’t ignore them!
- There’s never enough time to do and see everything, so make a plan and stick to it...but, don’t get so hung up on the plan that you can’t respond to new discoveries
  - Use the judgment of the crew on the surface to inform decision making
- Surface crew judgment on the tasks, and the time spent on doing them, tends to be better informed than the ground
- Navigation capability on the ground is a critical need
  - We solved this somewhat with the LRV using inertial navigation, but this is probably insufficient beyond 10 km
  - This applies to walking around as much as driving
- Use the proper tools and procedures for the right situation
  - Scale and the nature of the problem dictate the solution - train the crew to figure that out!
- Maximize crew flexibility
  - The crew skill mix we used on Apollo 17 is a good model for how to run crews with mixed capabilities and still maximize our science return, operational flexibility and safety on the lunar surface
- Automate science station deploys as much as possible, but leave room for human crew intervention
  - Nothing is perfect, and it’s embarrassing to have an automated widget fail, in part, because there’s no way for a human crewmember to fix it
- Keep your eyes open for unexpectedly useful things
  - LRV sampler, rake tool and the 500 mm Hasselblad were items that were not originally in the program, but were added due to both the flexibility of the system and the initiative of personnel
- Lunar dirt will be a pain, but it ain’t pixie dust - it doesn’t float around in vacuum, or have magical, instantly toxic properties
  - If we study the record of mine operators, quarry operators, and other industrial settings that have similar issues with airborne granular silicates, we’ll solve the lunar dirt problem
“Kennedy’s Apollo was not a spacecraft, not an engineering project, not a means to adding to man’s scientific knowledge. Kennedy’s Apollo was a heap of chips pushed to the center of the table.”

From “Apollo: The Race To The Moon”
Charles Murray and Catherine Bly Cox
Acknowledgements and Additional Material

This talk benefited greatly from discussions with Paul Spudis, John Gruener, Kent Joosten, and (in times past) Nancy Ann Budden, Steve Hoffman, John Young, Harrison Schmitt and Jay Greene. Any factual or interpretation errors are, however, mine.

There are a lot of sources of historical information about Apollo, not all of which I’ve read or studied. I list below my favorites, although this is not an exhaustive list. Some of these are out of print, but can be found on Alibris or Amazon.com:

- “A Man On The Moon: The Voyages of the Apollo Astronauts, by Andrew Chaiken, Viking Press.