FEATURE

Deep Space Navigation: The *Apollo VIII* Mission

by Paul Ceruzzi

In December 1968 the *Apollo VIII* mission took three astronauts from the Earth to an orbit around the Moon and back again, safely. It was the first mission to carry human beings far enough away from the Earth to be influenced primarily by the gravitational field of another heavenly body. That mission also marked a number of other famous milestones: the first human crew lofted by the Saturn V booster, the Christmas Eve reading from the Bible book of Genesis, and the famous *Earthrise* photograph showing a blue Earth rising above a barren and forbidding lunar horizon.

The mission was a triumph of long-distance space navigation. The flight plan called for the astronauts to arrive at the Moon and establish an orbit that swooped to an altitude of only about 110 kilometers (60 nautical miles, as NASA preferred to measure it) above the lunar surface, after a journey of nearly 400,000 kilometers (km). They achieved that nearly perfectly. That was no small feat, as the astronauts were well aware. If their velocity was a few percent too low, they would have crashed into the Moon on its far side, out of contact with controllers back on Earth. A few percent too fast, and they would swing into an erratic orbit, unable to get back to Earth. In an interview conducted in 2001 by Steven E. Ambrose and Douglas Brinkley, Neil Armstrong noted that as he and his fellow astronauts were being introduced to the basics of a mission to the Moon, the navigation problem was one of the biggest concerns that he had:

> Well I suppose that everyone would have concerns, but I don't know that they'd all be the same. People would worry about different things. I remember that one of the things that I was concerned with at the time was whether our navigation was sufficiently accurate, that we could, in fact, devise a trajectory that would get us around the Moon at the right distance without, say, hitting the Moon on the back side or something like that, and if we lost communication with Earth, for whatever reason, could we navigate by ourselves using celestial navigation. We thought we could, but these were undemonstrated skills.[1]

When President John F. Kennedy challenged the nation to send a crew to the Moon and back before the end of the decade, navigation was among the biggest of unknowns. At the beginning of the 1960s, it was by no means clear that navigating to the Moon would even be possible. The *Pioneer 4* mission, launched in March 1959, indicated the scope of the problem. Its goal was to send a 30 kilogram (kg) probe close enough to the Moon to measure that body's radiation field, if any. The probe achieved enough velocity to escape Earth orbit, but due to a timing error in the cutoff of the booster, it passed by the Moon at a distance of about 27,000 km, beyond the range of its onboard sensors.

One of the first contracts NASA let in preparation for a lunar voyage was to the MIT (Massachusetts Institute of Technology) Instrumentation Laboratory, under the direction of Charles Stark Draper, for a navigation system. The Instrumentation Lab had an acknowledged expertise in inertial guidance techniques, having already developed inertial navigation systems for aircraft and submarines. For space, the lab had done some preliminary work on a Mars probe, never flown, for the Air Force Ballistic Missile Division. For a mission like Apollo, inertial navigation had several challenges. The first is that gyroscopes, which are at the heart of an inertial system, tend to drift and give erroneous readings. The second is that the system needs to account for the acceleration of gravity, which cannot be distinguished from the accelerations due to a rocket's thrust or any other accelerating force.

The drift problem, though serious, was manageable for intercontinental ballistic missiles (ICBM), whose rocket motors burn only for a few minutes. And insofar as the Earth's gravity field was well-mapped, it was possible to factor out gravity for missiles that remained within the Earth's gravitational field. Neither held true for Apollo, which had to travel for several days from Earth to the Moon, and which on arriving at the Moon, entered a gravitational field that was poorly understood.

Engineers had considered these problems and had some experience in dealing with them. For the 1957 study done for the U.S. Air Force, the Instrumentation Lab proposed that the approximately 150 kg robotic Mars probe carry "a space sextant to make periodic navigation angle measurements between pairs of celestial objects: the Sun, the near planets, and selected stars." Also in the 1950s, the Northrop Aircraft Corporation developed a long-range navigation system for its robotic "SNARK" guided missile, an air-breathing, atmospheric weapon that could navigate across the Atlantic Ocean to targets in the Soviet Union using an automatic star tracker. The Instrumentation Laboratory had developed another inertial system that operated for long periods of time, with corrections for gyroscopic drift. That was for ballistic missile submarines, which remained submerged and hidden as much as possible, thus precluding periodic sightings on stars, as surface ships might navigate. For these submarines, MIT designed a system called SINS: Submarine Inertial Navigation System. Because the SINS gyros would drift over time, the Navy developed the TRANSIT satellite system, which allowed the sub to get a fix on its position by a brief ascent and deployment of an antenna. No optical sighting of stars was necessary. TRANSIT was a radio, not optical system. It was one of the ancestors of today's satellite-based geolocation devices, although its method of providing a fix, by measuring Doppler shift, did not form the basis for the Global Positioning System and other modern satellite navigation systems.

Space Navigation, before Apollo

To return to Apollo: what else was known about navigation in space in 1961, at the time the contract with MIT was signed? The theory of space navigation for piloted spacecraft began with the same individual who pioneered in adapting seafaring navigation for aeronautical use: Philip Van Horn Weems (1889–1979). A graduate of the U.S. Naval Academy in 1912, Weems worked with Charles A. Lindbergh to develop methods of celestial navigation that Lindbergh and his wife, Anne Morrow Lindbergh, applied in their charting of trans-Pacific air routes. He is perhaps best known for his innovations in modifying chronometers, sextants, and other marine navigation devices and techniques for use onboard aircraft: innovations that saw wide use among U.S. air forces during World War II.

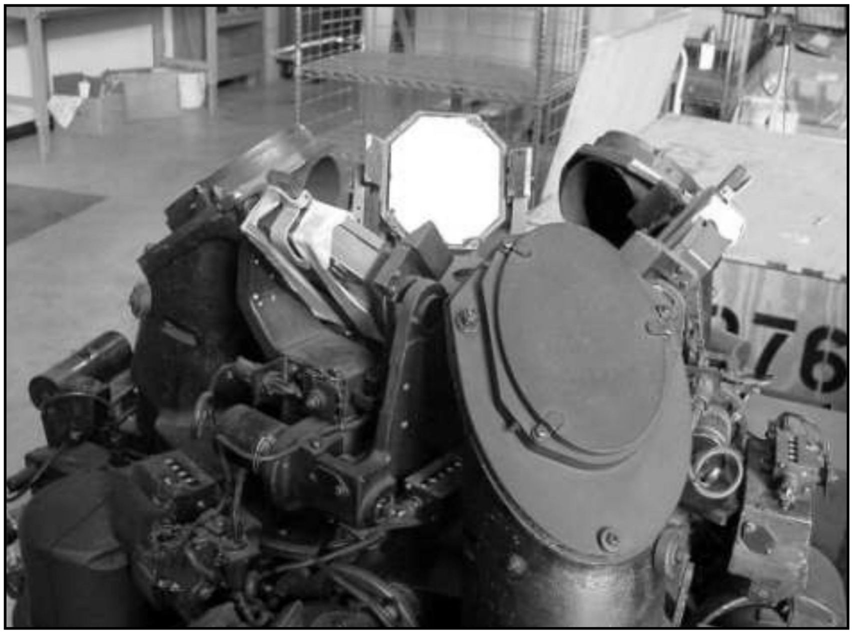
Weems retired twice from the Navy, but as the space age began in the aftermath of Sputnik, he was recalled to active duty at the rank of captain, and tasked with developing a course on space navigation for the U. S. Naval Academy.[2] The text that accompanies that course, the *Space Navigation Handbook*, was the work of many collaborators, but its overall tone, and much of the writing, is probably due to Weems. The course itself, a four-week course at the graduate level, was first convened in the summer of 1961, a few months after Soviet Union cosmonaut Yuri Gagarin's flight marked the dawn of human exploration of space. Weems developed aeronautical navigation as an extension of what seamen had done, taking into account the airplane's third dimension of altitude, its faster speeds, and other factors that precluded a simple extrapolation of existing techniques. For his first attempt at developing a theory of space navigation, Weems did the same, starting with what was known about aircraft navigation and extending it into space.

The techniques proposed in that course were quite different from those proposed by the MIT Instrumentation Lab for the Mars probe, or by Northrop for SNARK. Nor were they used for Apollo missions, even though they were centered on the astronaut's making observations of Earth, Moon, and stars from the spacecraft. One principle he developed was to determine absolute distance from the Earth (or Moon) by measuring the size of the observed disk, and to further determine the spacecraft's position in space by observing the star field behind the Earth of the Moon during such an observation. For trajectories close to the Earth, the spacecraft's altitude could be inferred by observing the amount of Earth's curvature. No inertial devices were proposed. Some amount of onboard computation was required, but Weems proposed, as he had done successfully for air navigation, to precompute solutions in advance and provide the astronaut with that data as printed tables or graphs. Weems was reluctant to employ an onboard electronic computer as at that time, circa 1961, such devices were neither reliable nor compact. (The SNARK guidance system, mentioned above, did have onboard computational ability, though it did not carry a digital computer. The device used vacuum tubes.)

"Earth Path Indicator," Project Mercury.
Credit: National Air & Space Museum

Among the navigational aids mentioned by Weems was an electromechanical "Position Finder" designed by Edwin Collen of the Kearfott Division of General Precision. (Collen called it an "Astronavigator," and that term will be used in this essay.) The device contained a small globe, a transparent hemispherical star chart that depicted stars as dots of luminescent paint, and an ingenious system of lenses and mirrors that allowed the astronaut to superimpose his observations of Earth and star field with those of the small globe and painted star field. When the two were aligned, the astronaut could determine a position in space and altitude above Earth. Collen proposed that Apollo astronauts carry such a device as an emergency backup to the main Apollo guidance and navigation system. NASA rejected the proposal, although it did develop a set of emergency procedures, some of which were used during the *Apollo XIII* mission.[3] For the early Soyuz missions, Soviet cosmonauts carried a similar device onboard to help them locate their position in orbit.[4]

For Project Mercury, NASA adopted an even simpler mechanical navigator, intended to assist the astronaut in returning to Earth. It consisted of a small globe rotated by mechanical clockwork, with an icon depicting the Mercury capsule suspended above it. On achieving a stable orbit, the astronaut would set the capsule's inclination and period of the orbit, as radioed up from the ground. The globe rotated under the icon to follow the rotation of the Earth, and another mechanism adjusted the orbit to account for the precession of the capsule's orbital plane. Thus the astronaut could follow a path as the icon passed over the



SNARK guidance system, with automatic star-tracker.
Credit: National Air & Space Museum

globe. John Glenn carried this "Earth Path Indicator" on the *Friendship 7* capsule in February 1962, but during that flight Glenn's naked-eye observations of the Earth were so good that NASA found the device redundant. It was carried onboard the following Mercury flight, piloted by M. Scott Carpenter in May 1962, and not used again.[5]

These examples of early space navigation devices illustrate an important point: the early 1960s was a time of enormous advances in the science and technology of spaceflight, including navigation. In those few years, engineers improved gyroscope technology and reduced drift. The mathematics of celestial mechanics, already well developed since the time of Newton, was directed toward practical spacecraft mission planning. Computers made a transition from vacuum tubes to solid state and became more powerful and more reliable. Ground-based computers remained large, but the development of high-level programming languages like FORTRAN made them more capable of handling complex mathematical problems. Large-diameter radio antennas were placed into service and provided an ability to track spacecraft into deep space. Atomic clocks were developed that were many times more accurate than the quartz-based clocks in use in the 1950s. Finally, with each Mercury and Gemini flight, NASA gained valuable data on the performance of navigation techniques by real-world experience. This was true throughout the decade but was especially pronounced as the Gemini program transitioned to Apollo.

With President Kennedy's end of the decade goal rapidly approaching, Apollo engineers had to make decisions about the craft's design and "freeze" it even as, for example, the *Gemini XI* mission, in September 1966, set an altitude record by coupling a Gemini spacecraft to an Agena and boosting its orbit to the edges of cislunar space. Thus, although the Gemini inertial platform used four gimbals, Apollo used only three, a simpler system that however could lead to a condition known as "gimbal lock."[6] Under normal conditions the crew could avoid gimbal lock, although in the *Apollo XIII* mission, gimbal lock was a persistent and recurring threat. Note that astronaut James Lovell, who flew on both *Apollo VIII* and *XIII*, was also a veteran of two Gemini missions: *Gemini VII* and *XII*; thus he had extensive experience with both designs, and clearly favored the four-gimbal system. In most instances, however, Apollo was able to take advantage of advances in technology made earlier in that decade, most notably Apollo's use of integrated circuits in its guidance computer. But in some cases the *Apollo VIII* mission carried with it some of the legacy of decisions made earlier in the decade based on conditions that had changed.

The MIT Instrumentation Laboratory's Approach

Weems's work laid a foundation for thinking about navigation in space at a time when only a few steps had been taken into that realm. By the late summer of 1961, when NASA awarded the first contract to the MIT Instrumentation Lab for Apollo navigation and control, a different approach to navigation emerged.[7] Central to Weems's approach was the determination of one's distance from the Earth by measuring the angle of the Earth's disc as seen from the spacecraft. The Instrumentation Lab's approach was more traditional: to measure the angle between the Earth's horizon and a star or between two stars.[8] These techniques were initially developed under an Air Force contract for a robotic mission to Mars, never flown. After 1958, the new civilian agency NASA took over planning for deep space missions from the Air Force. In November 1959, NASA directed the Instrumentation Lab to work with the Jet Propulsion Laboratory in Pasadena, California, to plan deep space, robotic missions. But according to David Hoag of the Instrumentation Lab, the two laboratories diverged in their approaches to navigation; with JPL focusing less on onboard techniques and more on navigating by precise radiometric techniques from the ground.[9] This divergence would reappear during the human Apollo missions out of Earth orbit, as we shall see.

The approach adopted by the Instrumentation Laboratory is best described as an inertial system, periodically corrected by star sightings. The inertial component was based on the Lab's work on the guidance system for the Polaris submarine-launched ballistic missile, which did not need stellar correction, as it was designed to operate for a brief period of time. For Apollo, the position given by the inertial system would be corrected, perhaps twice a day, by sightings on the Earth, Moon, or the stars. For that purpose Apollo carried a sextant, manufactured by the Kollsman Instrument Corporation, which operated like a traditional maritime sextant in that the astronaut would adjust the device until the image of a known star was aligned with the image of, say, the Earth's or Moon's horizon. That angular datum was then fed into the Apollo Guidance Computer (AGC), which computed the spacecraft's position. The sextant did not look like a classic marine or even aircraft sextant, but that term was appropriate. It had two telescopes: one at 28 power and the other at unity power but with a wider field of view. The optics were also mechanically constrained in their movement because of the need for the telescopes to penetrate the pressure hull.[10]

The Instrumentation Lab developed a basic technique to correct for drift. The astronauts would key in the coded number of a given star, and the computer would then orient the spacecraft's optics so that the star was centered in the eyepiece of the telescope. Depending on how much the inertial system had drifted, the star would be found a short distance away from the crosshairs. The astronaut would center the image of the star, press a button, and the computer would note the amount of drift. The process could be repeated against a second star if needed to realign the gyros.

Thus, although the Apollo navigation system was far removed from what Weems had envisioned a few years earlier, it replicated nautical techniques in use for centuries. It used a sextant. Both sailors and Apollo astronauts carried star charts. Sailors carried books of mathematical tables to assist them in converting observations into latitude and longitude; Apollo astronauts carried similar mathematical data, in this case precomputed and stored in the onboard computer. One should not push the analogy too far. Apollo was fundamentally an inertial, not a celestial system. Still, the notion of deep space as "this new ocean," in President Kennedy's words, must have been strong.[11]

Ground-Based Tracking

As the 1960s progressed, the end-of-the-decade deadline imposed by President Kennedy grew more urgent. Like many of the systems that made up Apollo, the development of the guidance computer was not easy. In particular, the software being written for the missions kept growing, overwhelming the memory capacity of the computer. Many of the accounts of the development of the system focus on the hardware, correctly emphasizing the breakthrough of using the newly developed integrated circuit, and the heroic efforts made to ensure reliability, while avoiding the complexity and weight of having redundant hardware (as the IBM-designed Launch Vehicle Digital Computer on the Saturn V had).[12] It turned out that a pacing element was the writing and testing of the software, especially as the AGC was tasked not only with navigation but also with controlling the service module rocket motor engines digitally (the Saturn V's rockets were controlled by a separate, analog computer).

The crisis came to a head in May 1966, at a meeting held at MIT and chaired by Howard W. ("Bill") Tindall of NASA.[13] As a result of this and other following meetings, a number of tasks for the AGC were eliminated, to save memory. And the question of providing a redundancy in the event of a computer failure was resolved by designating ground-based navigation techniques as the back-up to the onboard computer. This finessed the on-going debate about whether to have the computer repairable inflight by the crew, who would be provided with spare modules that they could install in the machine. Prior experiences, especially Gordon Cooper's Mercury *MA-9* flight of May 1963, indicated that making repairs to onboard electronic equipment created as many problems as it might solve.[14] Apollo would fly with only one AGC, sealed from the elements, and designed to work as reliably as possible. MIT engineers' memoirs of the Apollo missions stress this fact: the AGC had to work right the first time, and it did, throughout the program.[15]

Collen "Astronavigator"
Credit: National Air & Space Museum

Regardless of that decision, the need for onboard navigation ability remained, at least to navigate if communications with Earth-based stations were lost or degraded. There were also two major components of the Apollo missions that had to be controlled onboard. The first was to reduce the velocity of the Apollo configuration to enter into a stable orbit around the Moon. The physics of orbital transfer dictated that this be performed by a carefully controlled burn of the service module's engine behind the Moon, out of contact with Earth. As mentioned above, the resulting orbit was to have a pericynthion (the lunar equivalent of perigee for Earth orbit) of approximately 60 nautical miles, so this maneuver had to be executed correctly. The second function was the landing itself. The time delay of radio signals from Earth to the Moon is not much, on the order of a few seconds, but that was too long to entertain any notion of controlling the landing from Earth. Strictly speaking, this second function was a control, not a navigation problem, but the absolute requirement for onboard guidance and control capability meant that onboard navigation ability had to be present.

Although the AGC did not use redundant circuits, as the Saturn V Launch Vehicle Digital Computer used,

A Soviet Soyuz navigator
Credit: National Air & Space Museum

there were redundancies onboard. The lunar module (LM) carried an identical AGC, which could be used as a backup on the outward leg of the journey. It was unavailable for the return to Earth, as the LM ascent stage was jettisoned before that leg of the journey. (Note also that the *Apollo VIII* mission carried no LM on either leg of its mission.) The LM also carried an Abort Guidance System (AGS), intended to be used only to get the LM's ascent stage off the Moon and into lunar orbit quickly in the event of an emergency. The AGS contained a small digital computer of its own.[16] NASA rejected electromechanical backup devices, such as Edwin Collen's Astronavigator, but astronauts could navigate using sightings out the windows, with timing supplied by their mechanical analog wristwatches. Nearly all of these procedures, including the use of the LM's guidance computer, were used to bring the *Apollo XIII* astronauts home safely.[17]

The ultimate outcome of the meetings between NASA and the Instrumentation Laboratory was that ground-based navigation techniques would play a greater role.[18] By 1966, with the transition from Gemini to Apollo fully underway, the policy went beyond that: "The primary *navigation* system in cislunar space is the ground system [emphasis added]."[19] By that year, NASA had established a world-circling network of nine-meter (30-foot) antennas for tracking, communications, and control at sites around the globe. For Apollo, these sites were used for the Earth-orbital phase of the mission. To track the astronauts after leaving Earth orbit, only three sites with larger, 26-meter antennas, spaced approximately 120° longitude apart, were needed, although the 30-foot stations were also used. These were co-located near the three Deep Space Network (DSN) sites managed by the JPL for unpiloted missions away from Earth orbit.[20] The DSN and the Manned Space Flight Network (MSFN) had different missions but were complementary: each used 26-meter (85-foot) antennas, and links were established so that the DSN system could back up MSFN if necessary. The three stations were at Goldstone, California; Honeysuckle Creek, near Canberra, Australia (about 30 km away from the DSN Tidbinbilla station); and Fresnedillas, Spain, west of Madrid.[21]

The MSFN did not duplicate the much larger DSN 70-meter (230-foot) antennas, which the DSN required for trajectories far beyond the orbit of the Moon. The links between the two systems, however, allowed NASA to use them, in addition to large radio astronomy dishes, such as the 64-meter (210-foot) antenna at Parkes, Australia, if needed—a need that did arise on several occasions.[22]

The decision to use this network as the primary cislunar navigation system was because of more than just the limitations of the onboard AGC. One factor was political: by the mid 1960s, the fear that the Soviet Union would jam or otherwise interfere with communications between astronauts and the ground during a lunar mission abated. The space race was still on, and classified information about Soviet progress was communicated at least to James Webb, NASA administrator, at the time. The decade began with a sense that space would be a military theater much like air: with orbiting bombers poised to deliver bombs to targets on Earth, with interceptors shooting enemy spacecraft, and so on. That did not materialize. ICBMs travel through space on their way to a target, and space did become a theater for military reconnaissance and signals intelligence, but for military activities the human presence was found to be unnecessary, impractical, or not worth the cost. Although tensions remained high between the United States and the Soviet Union during the 1960s, as the decade progressed NASA came to believe that that the Soviet Union was not going to directly threaten U.S. human missions to the Moon, and the fear of jamming subsided.

Among the technical advances behind the decision was the development for Apollo of a unified system that combined all tracking, communications, uplinked commands, telemetry, and other control signals onto one band of frequencies in the S-Band, around 2,300 MHz.[23] This system was not in full operation at the time of the *Apollo VIII* mission, but enough was in use to allow more functions to be performed by Apollo's avionics without incurring a weight penalty or excessively complicating the spacecraft's design. A second technical factor was the rapid improvement in the accuracy of timing devices, beginning with the introduction of rubidium and cesium-based frequency standards in the late 1950s, which replaced quartz oscillators that had been in use since before World War II. By the late-1960s, cesium-based clocks attained a stability of nearly $1:10^{13}$ defined as the stability of the standard during a 24-hour period. That was nearly 100,000 times improved over quartz oscillators (and a million times better than mechanical chronometers).[24] For the Apollo missions, NASA's MSFN used a rubidium standard, not as accurate as cesium but stable enough to give very accurate fixes.[25] The best fixes were obtained using the 26-meter antennas on the ground, and the high-gain, S-band antenna located on the Apollo service module, with its distinctive array of four small parabolic dishes pointed toward Earth. A fix could also be obtained using the lower-power, omnidirectional antenna on the spacecraft, thus providing an additional layer of redundancy.[26]

The early 1960s also was a time of advances in radio communications and signal processing, which further contributed to meeting President Kennedy's challenge. Around the time of Sputnik, Eberhardt Rechtin of JPL was working on jamming, and defense from jamming, of signals for guided missiles. In the course of that work he turned to the classic mathematical work done by Norbert Wiener during World War II on the extraction of a meaningful signal in the presence of noise. Using that as a starting point, Rechtin and his colleagues came up with techniques that would allow one to track spacecraft with great accuracy from the ground, despite the weight and size restrictions that made it difficult for spacecraft to carry high-powered transmitters or large parabolic dishes onboard. One of the outcomes was the development of the Phase Lock Loop (PLL), which is now the standard method of reception employed by cell phones, GPS receivers, car radios, broadcast and satellite televisions, et cetera. In an interview conducted for the IEEE (Institute of Electrical and Electronics Engineers) in 1995, Rechtin recounted how experts told him that it would be impossible to receive meaningful information from deep space, as the weak signals would be swamped by background noise. The PLL used a narrow band receiver, which tracked the frequency of the transmitter even as that frequency shifted due to Doppler effects.[27] Rechtin was also among those who developed the concept of using a sequence of "pseudo-random" numbers—a sequence of digits that appeared to be random but that were known and specified in advance, to carry information. This, too, was an outgrowth of Norbert Wiener's work on the extraction of signals from noise, and would be developed by others into what has become known as "spread-spectrum" communications in common use today.

The ground-based navigation system used for Apollo employed these techniques. A pseudo-random code was sent to the spacecraft over the unified S-band. It was received, and retransmitted back to Earth on a slightly different frequency also within the S-band.[28] The time it took for the signal to go to and from the spacecraft, subtracting out the known times for the signals to travel within the equipment, divided by two, gave the absolute distance of the spacecraft from the dish, to within 2 meters.[29] The angle of the antenna as it focused on the spacecraft gave further information on the craft's position, to a few milliradians (about 1/10°). Finally, a measurement of the Doppler shift of the S-band frequency gave the radial component of the spacecraft's velocity relative to the ground station. By combining readings from different ground stations, plus similar readings taken during a span of time, the spacecraft's velocity and position could be determined in all axes.

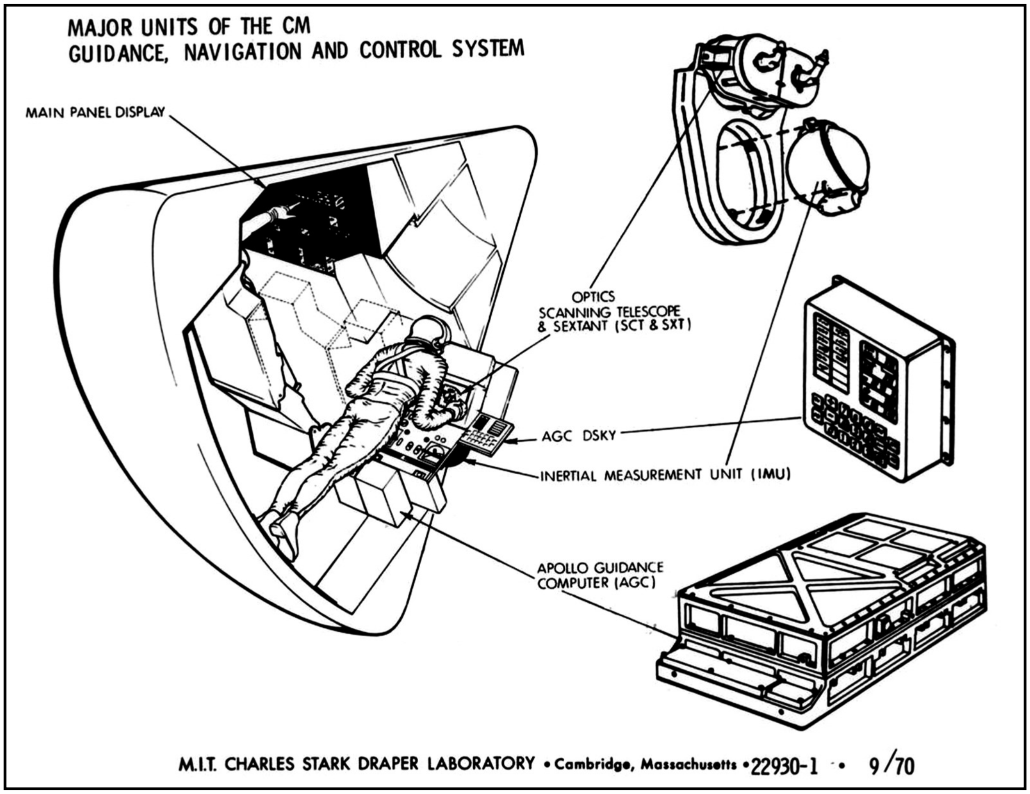
James Lovell, sighting through the Apollo sextant, *Apollo VIII*. His right hand hovers over a button, which marks the sextant's position as it is centered over a known star. On the upper right is the Apollo Guidance Computer's Display Keyboard (DSKY), one of two in the Command Module. Credit: NASA

It was the precision of the Doppler measurements that tipped the balance in favor of ground techniques. By an ingenious use of the telemetry codes, combined with using more than one ground station to track the spacecraft and the rubidium frequency standard, NASA was able to determine range to around 30 meters, and velocity to within 0.2 feet per second.

Simulations done before the *Apollo VIII* mission showed that tracking by the ground-based MSFN was more accurate during the initial phase of a mission, until about 35 hours after Trans Lunar Injection (TLI), when the spacecraft was about halfway between Earth and the Moon. From that point until the craft entered lunar orbit, the onboard system was slightly more accurate. MSFN-based tracking was also more accurate in determining position and velocity as the spacecraft orbited the Moon. That was because of the geometry of the Apollo's trajectory as it orbited the Moon; perhaps also to the irregularities of the Moon's gravitational field.[30]

These techniques determined the position of spacecraft beyond Earth's orbit with great accuracy. Two decades later, the Global Positioning System (GPS) would use the same techniques "inside-out" to determine the position of a person or object on Earth. GPS uses pseudo-random codes, and measures distance by measuring the time it takes a signal to get to a receiver from space. But the GPS system has the atomic clocks in space, not on the ground. And GPS knows the position of the satellites in space, not the receiver on the ground, to great accuracy.

Many histories of the Apollo program have focused on the remarkable capabilities of the AGC, with its novel interactive programming ability, its reliability, and its pioneering use of integrated circuits. Fewer have looked at the computers used on the ground to support the mission. NASA's computing facilities grew out of a Naval Research Laboratory facility on Pennsylvania Avenue in Washington, within sight of the Capitol. With the establishment of NASA in 1958,



Major units of the CM Guidance, Navigation, and Control System. Note the two DSKYs: one on the main panel, the other next to the scanning telescope and sextant. Credit: Charles Stark Draper Laboratories

the Space Computing Center moved to Greenbelt, Maryland, at the Goddard Space Flight Center. Beginning in 1960, Goddard computers, primarily IBM (International Business Machines) mainframes, calculated trajectories and orbits for robotic and early human flights. NASA was one of IBM's best customers, and it was able to do what few other IBM users could do, namely make fundamental modifications to the systems IBM supplied. IBM leased, not sold its computers, and it did not allow its customers that freedom. In a typical mainframe installation, programs were keypunched, transferred from decks of punched cards to tape, and the tapes ran through the computer to give an answer in printed form. IBM made an exception to that rule for NASA, which needed to be able to run the computers in "real-time": to enter in data directly and receive results as soon as the computer could calculate them. In other words, NASA modified the IBM machines to operate like a modern personal computer, even if the machine cost a million dollars and required an air-conditioned room of its own .

For Project Mercury, NASA created a "Mercury Monitor" system that could operate this way. By the mid-1960s, NASA–Goddard continued to manage space communications, while navigation and trajectory analysis were transferred to the Real Time Computation Center (RTCC) at the Manned Spaceflight Center (MSC) in Houston. Initially the RTCC used a set of IBM 7090-series mainframes, which were replaced beginning in 1966 by IBM's third-generation System/360 computers.[31] The term "third generation" implied that they used integrated circuits (IC). The System/360 used a hybrid circuit called "Solid Logic Technology," which combined a number of discrete components onto a small ceramic substrate. (The AGC circuits used silicon and were a direct ancestor of the ICs in use today). The new-generation IBM mainframes were a large advance in the state of computing art. They not only had faster processing speeds and more memory, they also came with more sophisticated software. Programmers at MSC developed a customized operating system that allowed Houston controllers to operate the computers in both batch and real-time mode. Called HASP (Houston Automatic Spooling Priority; SPOOL was itself an acronym related to input/output functions), it not only served NASA well but also was offered as a product by IBM to other customers.

Creating an operating system for a machine as complex as the System/360 was perhaps one of the most challenging tasks in all of computer programming. The fact that NASA was able to do this so well, while its main focus was getting human beings to the Moon, is testimony to the space agency's talent.[32] These systems created an effervescent atmosphere in Houston, as mathematicians combined centuries-old equations of celestial mechanics developed by Isaac Newton, Pierre-Simon Laplace, Carl Friedrich Gauss, and others, with new techniques tailored for space missions and taking full advantage of the number-crunching ability of IBM's hardware.

Apollo VIII

These concepts and simulations were put to the test on the morning of 21 December 1968, with the launch of a Saturn V rocket, carrying a crew of three astronauts, from Pad 39A of the Kennedy Space Center in Florida. About 38 minutes after launch, and while still in low-Earth orbit, command module Pilot James A. Lovell Jr. jettisoned the protec-

Apollo Guidance Computer DSKY on the main panel, during a ground simulation.
Credit: NASA

tive covers from the command module optics, in preparation for a preliminary alignment of the spacecraft's inertial platform.[33] When he looked through the telescope, he saw a field of bright particles that made it hard to locate stars. The particles were probably small pieces of debris that came off the spacecraft when the covers were ejected. Later on during the mission there would be other sources of highly-reflective particles that would complicate the procedure. The crew also found it necessary to dim the cabin lights so that Lovell's eyes could identify objects in space. It took some time, about 15 minutes, to sort out the procedures, but Lovell was able to locate two stars, center them in the optics, and command the onboard computer to realign the gyros.[34] Lovell's readings, plus the computer's calculations, aligned the gyros to within .01° of what ground-based tracking indicated. "Pretty good for a beginner here," remarked lunar module Pilot William A. Anders.[35]

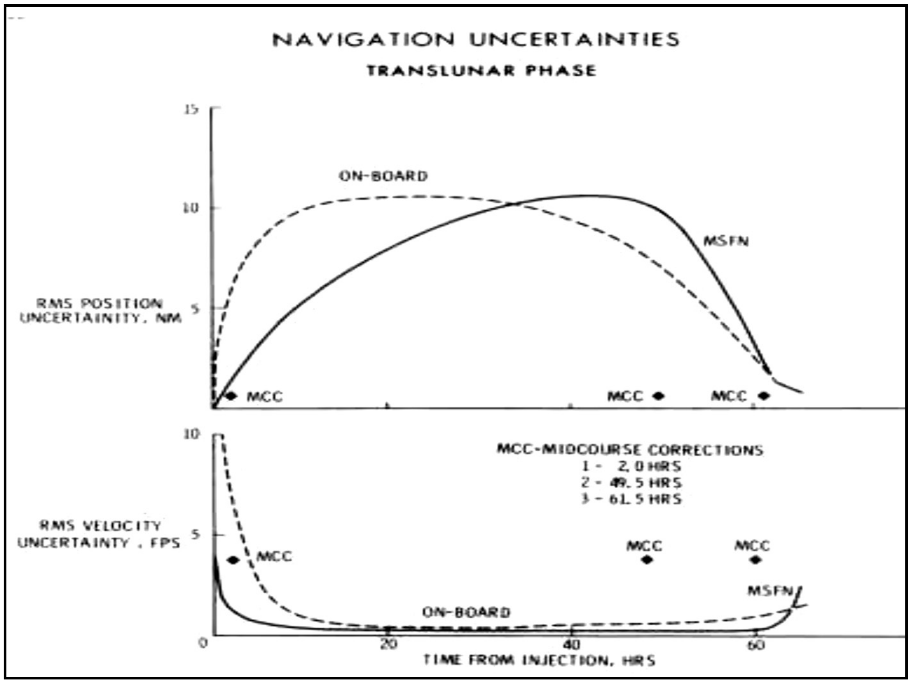
The real test of the system came later, after the crew left Earth orbit. After the launch and subsequent injection into Earth orbit were determined to be successful, Michael Collins, from his console at Mission Control in Houston, gave the crew the go ahead to restart the Saturn's third stage and send the astronauts to the Moon. Collins gave the message "*Apollo VIII*, you are go for TLI [trans-lunar injection]" at about two hours and 27 minutes after launch. At two hours, 50 minutes, the third stage of the Saturn V fired again for about five minutes, which increased its velocity, and the command and service modules attached to it, enough to reach the vicinity of the Moon.[36]

As might be expected for *Apollo VIII*, the crew and mission controllers in Houston had to adapt and modify their plans as the mission proceeded. The TLI burn was executed perfectly, as was the separation of the Apollo command and service modules from the Saturn V third stage. The schedule then called for the crew to take readings on stars and check the Inertial Measurement Unit (IMU) alignment shortly after separation, but the crew found that the third stage was flying in formation with them a little closer than expected, and they spent a bit of time ensuring that there would not be a collision. That put them behind schedule, but with the Moon several days away, it was not a critical delay. At about five hours into the mission, ground controllers directed the third stage to dump its residual propellants and other fluids, to prevent a possible explosion. That had the additional effect of pushing the stage away, although that had to be carefully choreographed. The procedure, however, dumped a lot of small particles into the region around it, and as the Sun reflected off them, the astronauts once again had trouble distinguishing between the particles and stars.

Partly for that reason, a procedure to calibrate the Apollo optics was scrapped, and the crew proceeded directly to take sightings and feed that information to the IMU.[37] The resulting readings were way off what the ground tracking had indicated. Mission controllers decided to ignore the readings. At this point a second complication arose: the mission plan called for the crew to rotate the command service modules (CSM) slowly, to even out the effect of solar radiation (called "Passive Thermal Control," better known as "barbecue mode"). That had to be postponed, as it would conflict with the need to hold the CSM to a precise attitude to locate a star. [38]

Eventually all of this was worked out. The crew managed to remove the bias from the optics, find stars, and take good readings. Working with ground controllers, they learned how to roll the spacecraft for Passive Thermal Control, and stop it when necessary to point the telescope at a target. By about 12 hours into the mission, the onboard navigation calculations, carried out by the AGC, were in close agreement with the ground-tracking data. All indications showed that when the astronauts arrived at the Moon, they would skim above its surface--but not hit it—and thus be able to fire the service module's engine to put them into a safe and stable orbit around the Moon.

As the crew got closer to the Moon, their navigation readings got progressive-



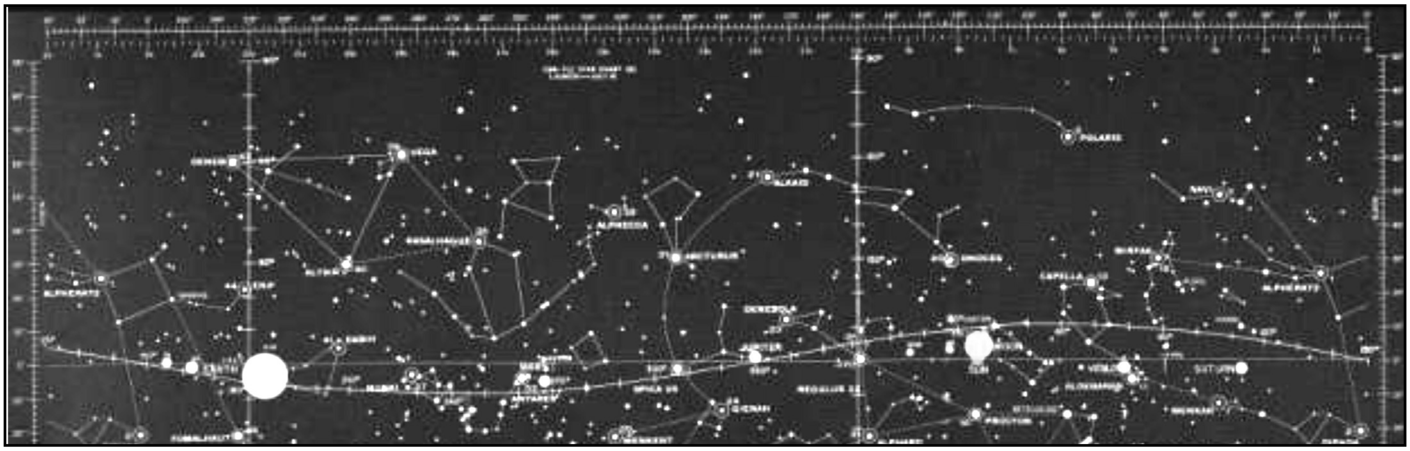
Comparison of ground-based (MSFN) and on-board (AGC) navigation accuracy at various phases of a mission, projected in simulations, 1966. (Ref: *Proceedings*, Apollo Lunar Landing Symposium, June 25-27, 1966, Houston, Texas, NASA, NASA-S-65-10006; fig. 24. Credit: NASA

ly easier. Early in the journey, sunlight reflected from the Earth washed out some of the sightings through the telescope; this diminished as the Earth receded. The spacecraft continued to be surrounded by stray particles, including ice crystals after a urine dump, but it became easier to distinguish between these and the stars. Also as the Earth receded and as Lovell gained practice, he was more consistent in sighting the Earth's horizon, which was indistinct because of its atmosphere. A reading of the angle between the Earth's horizon and a star, taken at 17 hours, 53 minutes, into the mission, matched perfectly with what the onboard computer indicated. Lovell exclaimed, "How's that, sports fans? All balls." To which Anders replied, "As soon as you've got an audience, you do great." ("All balls" was the astronaut's way of saying the computer DSKY—data storage and keyboard—was displaying all zeroes, that is, no error.)[39] On the return journey, the onboard MIT navigation system continued to work perfectly. The mid-course corrections were minimal, and the onboard navigation readings matched those from MSFN exactly. Near the end of the mission, around the time of the final mid-course correction, Astronaut Jerry Carr, on duty as capsule communicator at Mission Control, joked that Lovell's head was getting swollen because of the good job he was doing: "I hate to tell you this Frank [Borman], because Jim probably won't even be able to wear his comm. carrier [his communications headset] anymore, but that last set of marks put your state vector right on top of the MSFN state vector."[40] This banter between the crew and Mission Control reflected the fact that the *Apollo VIII* mission, which began with so many unknowns and risks, was turning out to be a huge success. It met all its objectives and gave NASA confidence that President Kennedy's goal to land a man on the Moon would in fact be met.

However, there is more to this story, and to understand that we go back to an exchange between the crew and Mission Control at about nine hours into the mission, as *Apollo VIII* was preparing for its first mid-course correction. The spacecraft was on a very good course, but mission planners decided to allow it deliberately to drift a little farther than necessary before making a correction, so that the mid-course correction could be made with the service module's SPS (service propulsion system) engine, rather than the small thrusters that would have sufficed for a small correction. This allowed NASA to test the engine, which had to perform a critical maneuver behind the Moon twice: once to get *Apollo VIII* into lunar orbit, and again to bring it home. Because *Apollo VIII* was not carrying a lunar module, there was no redundancy; the SPS engine had to work.[41]

This test of the SPS engine was critical, on which the success of the mission, and with it President Kennedy's goal, depended. Reading between the lines of the conversations between the crew and Mission Control, one senses the tension that everyone was feeling. There was none of the good-natured banter as the crew prepared for this burn. Before the mid-course correction, it was necessary to get as accurate a fix on the spacecraft's position as possible, and the crew methodically took readings and entered commands into the computer. They found, to their relief, that the resulting navigational fix from the onboard system was in close agreement with the state vector computed on the ground. Now came a critical decision for mid-course correction: which to use?

NASA decided that the tracking from the ground would take precedence. At about 10 hours into the mission, and an hour before the critical mid-course correction, Frank Borman asked Mission Control if it was time to realign the onboard platform. From his console in Houston, Capsule Communicator Mattingly said, "That's negative, *Apollo VIII*. We would like to update things first, and we're going to give you an LM state vector and then an external Delta-V."[42] What that meant was that NASA would transmit the craft's state vector—the set of numbers describing its position and velocity—from ground-based, or external, data taken from its tracking network, and store that into a portion of the AGC's memory location that was available because there was no LM on this mission. That state vector would be used as the basis to compute the mid-course correction. Borman keyed in the "Verb" P00 into the computer, which essentially told it to suspend all other program execution. He then flipped a switch, located just to



Apollo 11 star charts. This was prepared especially for the position of the stars, Earth, Sun, and Moon at the time of the *Apollo 11* launch, July 1969. Slightly different charts were prepared for Apollo VIII and would have been carried onboard. Note the two-digit numbers for many of the stars—these numbers were keyed in as a "noun" into the Apollo Guidance Computer's DSKY. Credit: NASA

the left of the navigation station's DSKY, from "Block" to "Accept": allowing the computer to receive and store the data being sent from Earth.

For the rest of the *Apollo VIII* mission, and for all Apollo missions thereafter, ground navigation data took priority for all navigation maneuvers outside low Earth orbit. Ground navigation took priority on all subsequent missions. It was especially critical during the *Apollo XIII* mission of April 1970, when an explosion cut off power to the CM, leading to the powering down of the CM's guidance computer. The crew—which coincidentally included James Lovell—used the LM computer for guidance, but not for navigation. Using a combination of ground commands, plus onboard mechanical aids and mechanical wristwatches, they were able to safely reenter the Earth's atmosphere and land within a few kilometers of the intended landing point.[43]

The *Apollo VIII* astronauts realized the dream of autonomous human space travel, in which spacefarers followed in the footsteps of Captain Cook, or the Lewis and Clark expedition.[44] Although they did not land on the Moon, their accomplishment will stand for all time as one of the greatest in the annals of human exploration. But we must also remember that the dream lasted only about seven hours: from the time the crew was given a "Go for TLI," at three hours into the mission, to flipping the switch to "Accept" at ten hours into the mission.

As of this writing, no human beings have had to navigate outside the close range of Earth since *Apollo XVII* in 1972, but one may assume that such missions will resume eventually. When they do, how will the crew navigate? Since 1972 we have seen remarkable achievements with unpiloted deep space probes hitting very precise targets at the moons of outer planets, asteroids, and comets, beginning with the *Mariner 10* mission to Venus and Mercury in 1974. But we may also assume that there have been advances in onboard, stellar-inertial techniques also. Whether the dream of autonomous space exploration can be revived remains to be seen .

About the Author

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Notes

1. Neil A. Armstrong, interview with Dr. Stephen E. Ambrose and Dr. Douglas Brinkley, *Quest* 10, no. 1 (2003): 6–45; quote on 29–30.

2. [U.S. Navy], Space Navigation Handbook, NAVPERS 92988 (Washington, DC: U.S. Government Printing Office, 1962), i.

3. Edwin Collen, private communication to the author. Collen donated the prototype Astronavigator to the National Air and Space Museum, catalog number A 1993-0078-000.

4. One of the devices, used by cosmonaut Vladimir Shatalov and carried on Soyuz 4 in 1969, is on display at the National Air and Space Museum.

5. During his tenure in the Senate, Glenn displayed an Earth Path Indicator (EPI) on a credenza behind his desk. The EPI in the National Air and Space Museum collections, catalog number A 1972-1170-000, was taken from an earlier, robotic Mercury flight.

6. David Hoag, "The History of Apollo Onboard Guidance, Navigation, and Control," Ernst A. Steinhoff, editor, *The Eagle Has Returned* (American Astronautical Society, supplement to *Advances in the Astronautical Sciences*, vol. 43, 1976), 277.

7. David A. Mindell, *Digital Apollo: Human and Machine in Spaceflight* (Cambridge, Massachusetts: MIT Press 2008), 106–107.

8. Hoag, "The History of Apollo," 270–300.

9. Hoag, "The History of Apollo," 271.

10. Although it was not difficult to maneuver the stack while coasting, during an observation the crew had to suspend the so-called Passive Thermal Control, or "barbeque mode": the slow rotation of the craft to even out the heating of solar radiation.

11. President Kennedy used this phrase at a speech at Rice University in Houston on 12 September 1962. Although not the case with Apollo, note that the Space Shuttle orbiters were named after ships of discovery. The Shuttle *Enterprise* was named after a fictional spacecraft from the television series *Star Trek*. But that *Enterprise* was itself named after a ship.

12. Eldon C. Hall, *Journey to the Moon: The*

One of the NASA 26-meter MSFN antennas collocated with similar 26-meter, and much larger 70-meter antennas of the Deep Space Network. The DSN was developed for uncrewed missions far beyond the orbit of the Moon. A link established between the DSN antennas and the Manned Space Flight network, and this link was pressed into service to obtain live television images of the *Apollo 11* landing, as well as emergency communications during the *Apollo XIII* missions. Credit: NASA

History of the Apollo Guidance Program, AIAA, 1996

13. Hoag, "The History of Apollo," 290.

14. Chris Kraft, *Flight: My Life in Mission Control* (New York, Dutton, 2001), 182–183.

15. Hoag, "The History of Apollo," 284.

16. James Tomayko, *Computers in Spaceflight: The NASA Experience* (New York: Marcel Dekker, 1987), 59–60.

17. John L. Goodman, "*Apollo 13* Guidance, Navigation, and Control Challenges," *Proceedings AIAA Space 2009 Conference and Exposition*, Pasadena, California, September 2009.

18. "More Apollo Guidance Flexibility Sought," *Aviation Week and Space Technology* (16 November 1964): 71–72.

19. Robert C. Duncan, "Apollo Navigation, Guidance and Control," Houston, Texas: NASA, Manned Spaceflight Center, *Proceedings and Compilation of Papers, Apollo Lunar Landing Symposium, 25-27 June 1966*, unpaginated. Emphasis in the original.

20. Sunny Tsiao, *"Read You Loud and Clear!": The Story of NASA's Spaceflight Tracking and Data Network*, (Washington, DC: NASA, 2008), NASA SP-2007-4232, 146.

21. Tsiao, *"Read You Loud and Clear!"*, 146–147.

22. Live television during the *Apollo 11* landing was received by the large antennas in California and Australia.

23. Myron Kayton, editor, *Navigation: Land, Sea, Air, and Space* (New York: IEEE Press, 1990), 317–331.

24. William G. Melbourne, "Navigation between the Planets," Kayton, editor, *Navigation*, 337. The author notes that project Mercury kept time using the National Bureau of Standards radio station WWV, accurate to about one millisecond.

25. Rubidium clocks were estimated to keep time to within one second in 30 years, about 1,000 times less accurate than cesium.

26. Duncan, "Apollo Navigation, Guidance, and Control," *Proceedings*. During the *Apollo XIII* mission, the hi-gain antenna, located on the damaged service module, was unusable. The astronauts communicated with low-power transmitters located on the command and lunar modules, through the 70-meter DSN antennae pressed into emergency service.

27. Eberhardt Rechtin, interview with Frederik Nebeker, IEEE Center for the History of Electrical Engineering, 23 February 1995, accessed at http://www.ieeeghn.org/wiki/index.php/Oral-History:Eberhardt_Rechtin.html. Reprinted in *Quest* 15, no. 2 (2008): 20–39.

28. The downlink carrier frequency was 240/221, or about 1.09 times the uplink frequency. Kayton, *Navigation*, 320.

29. Kayton, *Navigation*, 320.

30. Duncan, "Apollo Navigation, Guidance, and Control," *Proceedings*, figures 23, 24, and 25.

31. Paul Ceruzzi, *A History of Modern Computing*, second edition (Cambridge, Massachusetts: MIT Press, 2003), 122–124.

32. It was a task that IBM itself failed at least once in doing; see Frederick P. Brooks Jr., *The Mythical Man-Month: Essays on Software Engineering* (Reading, Massachusetts: Addison Wesley, 1975).

33. *Apollo 8 Flight Journal,* transcript, http://history.nasa.gov/ap08fj/index.htm, accessed 25 January 2010; 54–55.

34. The command was "P-52": a two-digit "verb" that the AGC interpreted to mean to realign the platform based on the star sightings.

35. *Apollo 8,* transcript, 67, Mission Elapsed Time (MET) 000:56.

36. *Apollo 8 Flight Journal, http://history.nasa.gov/ap08fj/index.htm accessed 25 January 2010,* also Robert Godwin, editor, *Apollo 8: The NASA Mission Reports* (Ontario, California: Apogee Books, 2000), 178–179.

37. *Apollo 8*, transcript, 158, MET 5:08 and following.

38. *Apollo 8*, transcript, 158, MET 5:36.

39. *Apollo 8,* transcript, 273, MET 17:53:25.

40. *Apollo 8,* transcript, 1056, MET 123:31:14.

41. Kraft, *Flight*, 298. According the Kraft, the decision was his, after some dissent among other NASA controllers.

42. Kraft, *Flight*, 200; MET 9:54:35.

43. Goodman, "*Apollo 13* Guidance."

44. Note that this did not in any way diminish the importance of the AGC for control functions: that is, putting the craft into the proper attitude, or guidance functions: that is, ensuring during a rocket burn that the thrust vector is properly aligned with the craft's center of gravity as desired for a given trajectory.