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THE HISTORY OF APOLLO ON-BOARD GUIDANCE, NAVIGATION, AND CONTROL

by

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September 1976

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Cambridge, Massachusetts 02139

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When Apollo astronauts finally walked on the moon, thousands of engineers, scientists, managers, and technicians of many disciplines and specialties shared in the glorious accomplishment of an extraordinary national goal. This is the story of an essential part of that endeavor—that of the development and execution of the guidance, navigation, and control systems which, on-board Apollo along with the astronauts, made essential measurements of the motions of the spacecrafts and directed necessary maneuvers for the mission.

The Beginnings

The forerunner of the Apollo guidance, navigation, and control system, is found in an unmanned spacecraft and mission study started in 1957 by the Instrumentation Laboratory at MIT under a contract with the Air Force Ballistic Missile Division. The small Instrumentation Lab team for this study, led by Milton Trageser and supported by AVCO Corporation, the MIT Lincoln Laboratory, and Thiocol Chemical Corporation, produced a complete design of a 150 kg autonomous spacecraft which would take a close-up high resolution photo of Mars. This Mars probe had several novel features, later incorporated in the Apollo system, including a space sextant to make periodic navigation angle measurements between pairs of celestial objects: the sun, the near planets, and selected stars. The guidance technique utilized original formulations designed by Dr. J. Halcombe Laning and Dr. Richard Battin to operate a small rocket at appropriate times to put the spacecraft on a corrected trajectory which would utilize the Martian gravity during the close passage and thereby send the spacecraft with its Mars picture on a path back to earth for physical recovery. Spacecraft attitude control was to be accomplished by torquing small momentum wheels with the use of

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the solar pressure force on adjustable sun vanes to drive the average speed of these wheels toward zero. Overall autonomous operation was managed on-board by a small general purpose digital computer configured by its designer, Dr. Raymond Alonso, for very low power drain except at the occasional times needing fast computation speed. A special feature of this computer was the pre-wired, read-only memory called a core rope, a configuration of particularly high storage density requiring only one magnetic core per word of memory.

A four volume report of this work was published in July, 1959, and presented to the Air Force Sponsors. However, since the Air Force was disengaging from civilian space development, endeavors to interest NASA were undertaken. Dr. H. Guyford Stever, then an MIT professor, arranged a presentation with Dr. Hugh Dryden, NASA Deputy Administrator, which took place on September 15.* On November 10, NASA sent a letter of intent to contract the Instrumentation Laboratory for a $50,000 study to start immediately. The stated purpose was that this study would contribute to the efforts of NASA's Jet Propulsion Laboratory in conducting unmanned space missions to Mars, Venus, and the Earth's moon scheduled in Vega and Centaur missions in the next few years. A relationship between MIT and JPL did not evolve. JPL's approach to these deep space missions involved close ground base control with their large antenna tracking and telemetry systems, considerably different from the on-board self sufficiency method which the MIT group advocated and could best support.

The Instrumentation Laboratory report on the NASA study appeared in four volumes in April, 1960. It described the design of a 35 kg pod comprising a self contained guidance, navigation and control system intended for mounting on Centaur vehicles to support a variety of space missions. A space sextant, similar to but improved over the Mars probe study, was to make the autonomous navigation measurements. Two single axis gyros and an accelerometer were part of the design for angle and velocity change measurement. A wide ranging examination of deep space trajectory studies was reported by Laning and Battin to show needed injection velocities, transfer times, and target planet approach paths. A variable time-of-arrival guidance scheme was formulated by Battin to

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* Dryden did not hear their talks. The MIT Laboratory team was upstaged by the presence of Premier Kruschev that day visiting in Washington.

improve the maneuver fuel use. He also worked out strategies for optimum navigation measurement schedules with the sextant. Other features showed the development of ideas started in the Mars probe. Particularly the configuration of the digital computer was refined by Alonso and Laning.

Early Apollo

The inability of the MIT Instrumentation Laboratory team and its ideas to find a place in the unmanned deep space missions continued through the summer of 1960. In November, Dr. C. S. Draper, Director of the Instrumentation Laboratory, had conversations about this and about possible participation in manned space missions with Dr. Harry J. Goett, Director of NASA's Goddard Laboratories and Chairman of the NASA Research Steering Committee on Manned Space Flight.

The manned lunar mission had been under NASA consideration for some time and was being examined by Goett's committee. The Space Task Group at NASA's Langley Research Center formed in October, 1958, was working on Project Mercury but was by this time considerably involved in the proposed moon mission. The name Apollo was announced in July, 1960, and in August NASA stated its intent to fund six month feasibility study contracts which were later in the year awarded to General Dynamics/Convair, General Electric Company, and The Martin Company.

After the Draper and Goett conversation, a meeting at Goddard was held November 22, 1960, to discuss a six month $100,000 contract with the Instrumentation Laboratory for an Apollo study and preliminary design. The details were proposed by Trageser at MIT and Robert G. Chilton, of the Space Task Group at Langley. A technical proposal was submitted on December 23, and the contract started in February.

Trageser and Chilton developed the basic configuration of the proposed trial design which prevailed throughout the program. They determined the system should consist of a general purpose digital computer, a space sextant, an inertial guidance unit (gyro stable platform with accelerometers), a control and display console for the astronauts, and supporting electronics. The inflight autonomy of the earlier Air Force and NASA studies seemed appropriate to the manned mission, particularly since some urged that the mission should not be vulnerable to interference from hostile countries. It was judged important to utilize the man in carrying out his complex mission rather than merely to bring him along for the ride. In addition, a certain value to self-contained capability was envisioned for future deep space programs for other reasons: First, the finite electromagnetic signal transmission time makes fast responding ground remote control impossible. Second, it was envisioned that the country would eventually have many missions underway at the same time and it was important to avoid saturation of the large expensive ground stations.

The initial Apollo contract at the Instrumentation Laboratory studied certain navigation measurements easily made by a human such as the timing of star occulations by the moon and earth during the circumlunar voyage. Of significant importance, however, Battin devised a generalized recursive navigation formulation to incorporate each navigation measurement of any type as it was made, such as the star occulatation or a sextant measurement, so as to update and improve in an optimum least squares sense the estimate of spacecraft position and velocity. Several navigation measurement schemes were formulated as experiments in hopes that they could be studied and verified by the astronauts soon to fly in Mercury.

Organization of the various NASA centers on Apollo was underway in November 1960, in Apollo Technical Liaison Groups coordinated by Charles J. Donlan of the Space Task Group. The Guidance and Control Technical Liaison Group first met in January 1961 under Richard Carley of the Space Task Group. The contract then being negotiated with the MIT Instrumentation Laboratory in the guidance and control area was acknowledged as needed to augment the Convair, General Electric, and Martin feasibility studies. At the second meeting in April 1961 this group started work on the preparation of the guidance, navigation, and control specifications for the Apollo spacecraft.

The following month on May 25, 1961, President Kennedy in a special message to Congress urged the nation to "commit itself to achieving the goal, before this decade is out, of landing a man on the moon..."

With the impetus of the presidential challenge, the efforts at the Instrumentation Laboratory changed character. The role the Laboratory would play depended not only on its earlier space studies but also the fact that another team was in place at the Laboratory, which had just accomplished a similar task to develop the Navy's Polaris missile guidance system on an extremely tight schedule. Ralph Ragan, who led that effort, immediately joined with Trageser, to work with Chilton to define an Apollo guidance, navigation, and control system to support a flight test as early as 1963. By July 1961, a task statement had been written and on August 10, by letter, NASA contracted the Laboratory for the first year's development of the Apollo guidance and navigation system. This was the first major Apollo contract awarded by NASA. The early start was justified by the central role this function would necessarily have. Key personnel from the Laboratory's Polaris Team joined Trageser who was named by Dr. Draper as Director of Project Apollo. Ragan became Operations Director, and David Hoag, having been Technical Director of Polaris became Technical Director of Apollo.

That same August, James Webb, NASA Administrator, invited Dr. Draper and members of the Instrumentation Laboratory Apollo Team to Washington for discussions. The meeting took place on the 31st at NASA Headquarters and continued at Webb's house for dinner that evening. In acknowledging the difficulty of guiding the lunar mission, two things concerned Webb. First he wanted to know when the guidance system could be ready. Draper provided the accurate forecast: "You'll have it when you need it." Second, he wanted assurances that the equipment would really work. In reply, Draper volunteered to make the first flight and run the system himself. Hardly anyone doubted his sincerity and in letters to NASA officials he repeatedly reminded them of his long experience of over 30 years in instrumentation design, as a pilot, and as a flight engineer. It was Draper's contention that although he himself was both a pilot and an engineer, it would be easier to train an engineer to be a pilot than to train a pilot in the necessary engineering.

The early conceptual work on the guidance and navigation proceeded rapidly. Trageser, Chilton, and Battin had worked out the overall configuration which was to hold to the end. The many maneuvers both in orientation and in translation would require a full three axis inertial measurement unit with gyros and accelerometers. An optical system would be needed to align the inertial system periodically to the stars. The optical system was also necessary to make navigation measurements in a sextant configuration by observing the direction of the earth and moon against the background stars. A general purpose digital computer was required to handle all the data. And an arrangement of display and controls for the astronaut to operate the system would be needed. Considerable extension of navigation and guidance theory, trajectory analysis, phenominological and human limitations to visual sightings of celestial objects, electronic packaging options, materials characteristics, reliability and quality assurance procedures, and management methods all were identified for early study.

It was recognized from the start that the Instrumentation Laboratory would utilize industrial support contractors to augment its engineering team and to produce the designs coming from the engineers. This followed the successful pattern utilized in the development of the Polaris missile guidance system.

Meanwhile, NASA started the procurement process for the Spacecraft Principal Contractor. The request for proposal was issued on July 28, 1961. North American Aviation was selected on November 29 for the Apollo Command Module, Service Module, and boost vehicle adapter. Their contract excluded the guidance and navigation which was to be government furnished by the Industrial Support contractors of the Instrumentation Laboratory.

In early 1962 briefings to industry were made for the industrial support to the Instrumentation Laboratory for the guidance and navigation systems. Twenty-one bidders responded and three awards were made on May 8. A.C. Spark Plug Division, of General Motors, was given responsibility for the production of the inertial system, ground support equipment, and systems integration, assembly, and test. Kollsman Instrument Corporation was the industrial support for the optical subsystems, and Raytheon for the computer. Earlier, A.C. Spark Plug Division had been selected for the gyro production and Sperry for the accelerometer production, both to the Instrumentation Laboratory designs for these inertial systems components.

During this early 1962 period, the mission and its hardware were being further defined by NASA, North American Aviation, and the Instrumentation Laboratory. The Space Task Group had evolved into the Manned Spacecraft Center the previous October, and the selection of the Houston, Texas, site for the new center had been made. The Apollo Spacecraft Program Office was formed and managed by Charles Frick and Robert Piland. But a great controversy was underway, which had strong implications on the whole design process.

The existing mission plan included two large Saturn booster launches from earth, with an orbital rendezvous to assemble in earth orbit a large spacecraft for the lunar trip. This spacecraft would then be injected to the moon and would in its entirety land the three astronauts in the command module on the lunar surface using the propulsion of a large lunar landing stage. The guidance and navigation of this maneuver being studied at MIT incorporated a large periscope-range-finder so that an astronaut could view the lunar surface during maneuvers as he landed in the awkward position 25 meters up on top of the stacked spacecraft. The lunar landing stage would be left on the surface for the return; the Command Module being lifted on the ascent and return by the Service Module propulsion.

The alternate mission configuration, called Lunar Orbit Rendezvous, had been discussed for some time, particularly by John Houbolt and his colleagues at Langley. In this case, a single Saturn launch would inject a smaller spacecraft assembly towards the moon which included a relatively small Lunar Excursion Module for the actual landing, leaving the Command and Service Modules in lunar orbit. The return, of course, rquired a rendezvous in lunar orbit, which was considered by the critics of this scheme as particularly difficult and dangerous.

Finally in June 1962, the decision was made by NASA in favor of the lunar orbit rendezvous mission with its real advantages in weight and expense. The procurement process for the Lunar Landing Module was initiated in July and on November 7 Grumman Aircraft Engineering Corporation was chosen to design and build the Lunar Excursion Module.

With this, the Instrumentation Laboratory and the industrial support contractor tasks were expanded to include the guidance and navigation for the Lunar Module. Two additional guidance and navigation sensors would be required, however, which were assigned to Grumman. They were the landing radar, measuring the altitude and velocity of the Lunar Module with respect to the lunar surface, and the rendezvous radar to track a transponder on the Command Service Module to provide relative direction and range. Specifications for these radars were written by the Instrumentation Laboratory since the signals were to be used by the guidance and navigation computer in the Lunar Module.

It had been decided somewhat earlier that the first flight test, being scheduled for earth orbit exercises starting in the fall of 1963, and soon to be rescheduled to 1965, could not be met with a full guidance and navigation design capable of a lunar landing mission. For this reason, a Block I design was identified for the guidance and navigation equipment to support the first earth orbital flights. A Block II design was to follow for the later lunar flights. With the engineering help of the industrial support contractors, the Instrumentation Laboratory started design releases of production drawings for manufacture in July 1962, using a formal design review, release, and revision procedure which was followed throughout the program. (The last design release numbered 38,868 was made in 1975 to provide'the erasable memory load for the guidance and navigation computer in the last Command Module used to rendezvous with the Soviet Cosmonauts in the Apollo-Soyez mission.)

Hardware Design

The decisions that were being made early and rapidly for the guidance and navigation system were to have a lasting impact on the Apollo Program from the point of view of mission design.

The inertial measurement unit borrowed its technology heavily from the Polaris missile guidance experience at the Laboratory. John Miller assembled a Laboratory team and was supported by A.C. Spark Plug in the inertial system design. The mechanical design was undertaken by John Nugent, who had done that work for Polaris. In order to simplify the design considerably and to achieve more accuracy in the alignment to the stars, the inertial measurement unit was provided with only three degrees of freedom in its gimbals, although four gimbals would have permitted unlimited all-attitude freedom, With the natural choices for aligning the system for flight, only some unusual attitudes of the spacecraft would put the gimbals into lock where the alignment would be lost. The resulting constraint in the design irritated the astronauts, although, in retrospect, they had no particular trouble with the attitude limitations during missions,

It was the stellar alignment of the inertial measurement unit which made this design significantly different from that of the Polaris system which was erected with gravity and gyrocompass action.

The Apollo unit needed precision angle readout to the computer for each gimbal angle which would be compared with star sighting angles. The design of the inertial and optical angle interfaces to the computer was undertaken by Jerold Gilmore. The equipment, called the coupling data unit, included a complex arrangement of system operational modes among the inertial, optical, and computer hardware.

As the inertial system design developed, it came under attack as not having sufficient inherent or proven reliability to support Apollo in spite of considerable attention to this important issue. If a single gyro wheel stopped running or if a single gyro developed excessive drift instability, the mission could fail and the astronauts be endangered.

Many design, test, and operational techniques evolved and were utilized to achieve the final record: over 2500 hours in flight operations of the inertial measurement unit supporting all Apollo missions (over 7500 gyro unit hours) without any failures.

Philip Bowditch, Alex Koso, and others at MIT, along with engineering support from Kollsman, undertook the design of the optical system. Bowditch examined a number of configurations before a satisfactory sextant design was achieved. The instrument was configured with one of its lines-of-sight fixed along the axis of penetration of the spacecraft hull. This line was associated with the earth or moon side of the navigation angle. The other line-of-sight associated with the reference star was split from the first and tipped away by an articulating mirror in such a fashion that the navigation angle could be measured in any plane. The angle of tilt of the mirror, in conventional sextant fashion, was the desired measurement and was encoded for use by the computer navigation algorithms. The astronauts task was to control the orientation of the spacecraft so that the earth or moon was satisfactorily in the field of view, and then adjust the mirror and the measurement plane to get star image superimposed in his view on the selected earth or moon feature. In order to achieve the necessary 10 arcsecond accuracy of this measurement, the instrument was provided with a 28 power eyepiece. However the field of view was thereby so severely limited that a second independent, articulating instrument at unity power and wide field called a scanning telescope was provided which could serve as a finder for the sextant and to which its direction could be slaved.

Much attention went into the design of this wide field scanning telescope so that the astronaut would have a good chance of recognizing stellar constellations and identifying stars. The enormous problem came from scattered light in the instrument washing out the visibility of dimer stars. A really satisfactory engineering compromise among such things as the degree of articulation, the field of view, light traps, and sun shields was not found. Only with the spacecraft turned so that the optics were on the shady side and without the sun illuminated earth, moon, or other spacecraft in the field could a good view of the stars be obtained. This problem lessened in importance as actual mission techniques developed. An early concept required that the inertial system be turned off most of the mission time in order to save spacecraft power. It would be turned on, aligned, and used only during the guidance and control of rocket maneuvers. For a number of reasons the operations policy changed so as to leave the inertial system active throughout the mission. The procedure then became one in which periodically, perhaps twice a day, the inertial measurement unit drift in orientation was corrected to the stars. To do this, the computer would use the inertial unit angles to point the sextant star line approximately to the selected star. The gyro drift would be small enough, however, that the star would appear in the sextant field of view. The astronaut would then center the image, thereby giving the necessary data to the computer to realign the inertial unit. In this way accurate inertial alignment was maintained throughout the mission. Similarly, the computer could orient the spacecraft and point the optics close to any targets suitably specified by the astronaut.

The scanning telescope, in spite of the scattered light problem with stellar targets, provided an excellent tracking instrument for navigation sightings to the earth or moon while in orbit around these bodies. For this required function, line-of-sight rates were too fast to use the sextant. (Indeed, the precision of that instrument was not needed.) The navigation angle was measured by the computer between the prealigned inertial unit and the line of sight to the surface target being tracked by the astronaut.

The orientation relationships between the inertial unit and the optical lines of sight in this fashion demanded strict limits on the alignment and relative flexures between these instruments. Bowditch designed them both to be mounted to a common light-weight but stiff and stable structure called a navigation base. With a kinematic mount, spacecraft strains could be prevented from being passed on to twists in this navigation base. The complicating factor was that the optics objectives were in the hard space vacuum, while the eye pieces were in the one-third atmosphere cabin pressure. The total force of this pressure was about 3500 newtons and required careful consideration of the location of the force center with respect to the mounts. Relative motion was accommodated by a double walled metal bellows which provided the seal of cabin pressure.

Associated with the optics design was the question of the suitability of the earth and moon as navigation targets. Considerable theoretical and experimental work was undertaken early by Dr. Max Peterson, William Toth, and Dr. Frederic Martin. The moon, without an atmosphere, had crisp visual features and horizon when they were illuminated by the sun. The earth on the other hand might have most if not all of its suitable landmarks obscured by clouds at the critical time. The sunlit earth horizon, due to intense scattered sunlight in the atmosphere, is invisible from space and no distinct visual locator can be identified. Photometric equipment to measure the systematic change in brightness with altitude above the true limb in the blue part of the spectrum was designed into the sextant along with an automatic star tracker to solve this problem. Later in history, for reasons of cost and complexity, these were removed. The visual sightings of the earth horizon was reexamined for navigation use. Simulations with photometric fidelity of the situation were devised. It appeared that the human was capable of chosing some locator in the fuzzy horizon which he could duplicate with considerable accuracy. Before each mission, the navigator astronaut would come to the Instrumentation Laboratory to train on this simulator. With practice he could duplicate his sighting point within a few kilometers over the range of interest of distances to the earth. (Later on, early in his actual mission, he made several sightings to calibrate his horizon locator.)

The computer design was undertaken by Eldon Hall, who had designed the Polaris Missile Computer. Laboratory members assisting him included Dr. Raymond Alonso, Dr. Albert Hopkins, and Hugh Blair-Smith. In addition they were supported by engineers from Raytheon, who worked with Hall on the Polaris computer.

A compelling necessity was to design a reliable computer with sufficient capacity and speed yet with a very limited size, weight, and power drain.

The machine configuration chosen was a 16 bit, parallel, general purpose, real-time digital control computer. Initially configured with magnetic core-transistor logic, the change was soon made to an integrated circuit logic using technology being developed by the semiconductor industry. The deliberate choice was made to use only one type of integrated circuit logic, a three input NOR gate. Although wider variety could have substantially reduced the number of devices per computer, the resulting dedication in manufacture and quality control to the single circuit type gave important gains in reliability.

The fixed memory was the high density read only core rope developed in connection with the Mars probe. This meant that the contents of this indestructable memory had to be determined early in order to allow time for manufacture. Rather than a disadvantage, risky last minute changes of the program just before flight were physically prevented. A rope memory program was necessarily well tested before it flew on an Apollo mission.

A coincident-current magnetic erasable memory provided for temporary storage. The size was kept to a minimum both in the number of words and in the 16 bits per word, for low power consumption. The initial decision in the Block I design was 1024 words of erasable, but this was doubled for Block II based upon the experience in programming the earlier machine. Without changing the computer volume, the fixed memory likewise grew from an initial 12,000 words to 24,000 words in Block I to 36,000 in Block 11. To the programmers, even these larger numbers were to seem inadequate as the functions to be performed in the computer on the lunar missions expanded substantially over original forecasts.

Both memories, operating on a 12 microsecond cycle time, were configured to look identical to the program. A very limited basic instruction repertoire was expandable by powerful interpretive routines written by Charles Muntz which saved program word use at the cost of speed. Over 200 input and output circuits for numerous interfaces with other hardware were provided to perform the real-time control function. Certain descrete input and timing signals could be arranged to interrupt the program underway *so* that urgent tasks could be serviced in real time without the need of continuously scanning inputs.

A most important input/output function was provided by a display and keyboard and associated software control ingeniously designed by Alan Green. The keyboard allowed the input of the 10 digits and seven other coded functions on separate keys. The display included three, 5 digit numbers plus sign *to* indicate numerical data, and three, two digit numbers to identify the function being performed by numeric codes for "verbs," "nouns," and "program." The verb-noun format permitted a sort of language of action and object such as "display-gimbal angles" or "load-star number." The program number identified the major background computation underway in the machine.

With this display and keyboard the astronaut had enormous flexibility and power in communicating with and directing the computer's operation. Many hours of study and training time on real equipment were required by the astronauts.. An early reticence by crew members was in time replaced by enthusiasm and confidence in their ability to use the computer to manage many aspects of their mission. Dr. Draper's early statement about training engineers versus training pilots might have been true, but the astronauts with their pilot (and engineering) background developed a competence in the guidance and navigation of Apollo which could not have been surpassed.

The computer display and keyboard permitted the crew to operate most guidance, navigation, and control functions. In addition the left hand translation command controller and the right hand rotational command controller were used appropriately for these maneuvers when commanded manually for computer action. Those operations associated with the use of the optics in manually tracking earth, moon, and stellar targets and in making the navigation angle measurements had appropriate controllers near the eye pieces.

Many of the hardware design decisions were easily made in trade-off among members of the design team at the Instrumentation Laboratory. The experience of the industrial support contractors and their concern for manufacturing producability influenced many other decisions. Accommodations had to be made to recognize test, checkout, and mission operations of the astronauts and the ground mission control. The largest problem, however, was reaching agreement on those design features which were affected by and influenced the hardware design of the spacecrafts. This was embodied in the negotiations of the so-called interface control documents which were to be agreed upon and signed off. Then each party could proceed with the confidence that he was protected against changes on the other side of the interface from affecting his design.

Numerous "coordination meetings" were held starting in 1962 between the Instrumentation Laboratory and North American with NASA participation in order to negotiate these decisions affecting both parties in the design *of* the command and service modules. In early 1963 coordination meetings with Grumman concerning the interacting decisions on the Lunar Module started.

One complicating groundrule, which in the end returned enormous savings, was the self imposed groundrule of the designers that as much as possible identical guidance* hardware elements would be used in both the Command Module and Lunar Module. The difficulty with this was that a successful agreement with North American for the Command Module interface could be upset by a second negotiation with Grumman for the same piece of guidance hardware in the Lunar Module. The effort paid off in manufacture, test, and astronaut training. The big guidance items, the inertial measurement unit and the computer as they came of the production line could then *go* to either spacecraft. Most of the small hardware components of the guidance were similarly interchangeable when the same function was accomplished in each spacecraft. The guidance

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* From this point on, "guidance" will mean guidance, navigation, and control.

turned out to be the only significant hardware that had this interchangeability. Most other spacecraft elements of the Command and Service Modules were not useable on the Lunar Module and vice versa.

The first important interface to be negotiated was the location of the guidance equipment in the spacecraft. North American and the Instrumentation Laboratory first examined wall space to the left of the left hand couch where the astronaut could use the eye pieces to make sightings. The final location was on the lower wall at the foot of the center couch. This required that the astronaut using the equipment would have to leave the couch and stand in the lower equipment bay. For those stressful times when the crew were constrained to their couches, all the guidance equipment except the optics could be operated through the computer from the main panel within reach using a main panel computer display and keyboard. A particular worry about the lower wall location for the guidance and navigation was that the optics there penetrated the hull on the hot side of the command module during return through the atmosphere. Initially a door covering these optics with a heat shield was provided for protection but was later removed from the design when analysis showed the hardware could tolerate the stress with suitable additional design changes.

Once the guidance equipment was located in the spacecraft, James Nevins, Nugent, and Bowditch immediately started an overall configuration design and mockup *so* that quite early the astronaut operations with the equipment could be tested and revised as needed.

Because of the operational complexity of the mission, the first mockup included a film projector to display procedures, maps, and charts to the astronaut. However, as the design of the whole operation progressed and the logic of the crew operation with the computer evolved, the film viewer was removed from the design. Hand-held notebooks such as used in Mercury and Gemini would suffice.

The exercise of the mockup with a pressurized space suit emphasized a problem. With his helmet;. on, the astronaut could not get his eye close enough to the eyepieces to perform his sighting tasks. The solution was to design special eyepieces, necessarily bulky but with sufficient eye relief, which could be attached in place of the regular eyepices when sightings in the helmet were required. The storage of these large units was found conveniently in the space recently vacated by the film viewer.

The design verification of the guidance hardware was initiated by Ain Laats in his systems test laboratory using specialized test equipment to examine the first production units of the assembled system. Of particular concern was the interactions among the inertial and optical sensors, the computer, the computer software, and astronaut functions when working all together. One of the earliest computer programs called SUNRISE was coded for this function. Special computer control program routines, hardware test code, and prelaunch systems functions were developed in this activity by Thomas Lawton, Ain Laats, Robert Crisp, and others.

An early concern with equipment reliability produced requirements for inflight fault diagnosis and repair. The Block 1 design carried spare modules which could be plugged into sockets in place of failed modules. However, an event in the last Mercury spacecraft flight in May 1963, changed this inflight repair policy. On the 19th orbit the Mercury automatic control system failed so that astronaut Gordon Cooper had to fly the last three orbits of the mission manually. The diagnosis of the problem was moisture and corrosion of electrical connections due to the high humidity and contamination accompanying the human in his cabin. From then on Apollo hardware designs in the cabin were required to be sealed from moisture. This eliminated plug in spare modules since inflight usable connectors could not be satisfactorily sealed without weight penalties. However, even for fixed modules, the sealing led to weight increases because the packages had to withstand the large cabin pressure changes without buckling.

Without the inflight repair, the concern for reliability remained so that the initial Block II design provided for two identical computers in the command module operating in parallel €or redundancy. This seemed to be excessively conservative to Cline Fraiser, of the Guidance and Control Division in Houston, and he directed the return to the single computer concept. The wisdom of his decision was borne out in that no inflight computer failures occurred. The combined failure rate both preflight and on missions was a small fraction of that of any other computer designed then or since for aerospace application. Such near perfect reliability was achieved at considerable effort, attention to design, a deliberate constraint to a minimum number of different parts, a detailed engineering qualification of design and components, and 100% stress testing of the parts to be used in manufacture.

The concern for safety identified backup hardware. In the command module North American provided a simple, independent panel instrument with a single accelerometer which was called an Entry Monitor. Although never needed for backup use, it was useful to the astronauts as an independent means to watch the velocity change of maneuvers being made by the primary system. Similarly in the Lunar Module, Grumman provided through Hamilton Standard and TRW an independent abort guidance system for a safety backup and also used as an independent monitor of the primary Lunar Module system.

As work entered 1964, it appeared that necessary interface decisions between the guidance hardware and the spacecrafts were lagging. To meet this problem Dr. Robert C. Duncan, the Chief of the Guidance and Control Division at Houston, instituted and chaired a series of Guidance Implementation Meetings. The first meeting involving North American in the design decisions concerning the Command Module guidance system took place in June. Following meetings were held approximately biweekly until February 1965. A second set of meetings with Grumman on the Lunar Module guidance and navigation occurred at the same pace between September 1964 and April 1966. These meetings followed a tight agenda of technical issues to be resolved, and involved presentations by the spacecraft designer, the Instrumentation Laboratory, and occasionally other interested parties. Following this, Duncan either made a decision which was then incorporated in the appropriate Interface Control Document, or he requested further study and scheduled new presentations at a future meeting.

A very significant decision took place early in this period concerning the implementation of the spacecraft attitude control autopilots. Prior to this time, this function was to be performed by analog hardware under design responsibility of the spacecraft manufacturers. These analog autopilots, which flew the Block I spacecrafts, were satisfactory, but lacked flexibility and required extensive specialized hardware.

It was Duncan who made the decision in June 1964, that the autopilots should be done digitally utilizing the hardware of the guidance system. *To* accommodate these new tasks, the speed of the computer was doubled and a much larger instruction repertoire was provided. Input and output interfaces also had to expand in order to send signals appropriately to the individual attitude jets, to the main engine gimbals, and to the thrust level servos, and in addition to receive the appropriate feedback signals from some of these elements. The memory capacity had been increased earlier for the lunar mission and was considered adequate for the autopilots.

Duncan's decision came with considerable controversy. The antagonists had shown that even expanded, the computer memory was insufficient and the computer was too slow to perform the necessary wide bandwidth control. They were right if one used the digital computer to perform digitally the same data processing handled by the analog circuits. The advocates argued that the proposed implementation would capitalize upon the flexibility, and nonlinear complex computations, natural to a digital computer. It was the right decision. By skillful design only 10% of the computer memory was devoted to the autopilots and only 30% of computer computation time was needed during times of high autopilot activity. A significant amount of complex hardware was eliminated, and moreover, the flexibility of the digital computer delivered better control performance and considerable improvements in efficiency in conserving the spacecraft fuel. The designs were the product of Dr. William Widnall, Gilbert Stubbs, and George Cherry at the Instrumentation Laboratory and Dr. Kenneth Cox at the Manned Spacecraft Center.

With the satisfactory conclusion of the hardware Implementation Meetings, the designers were able to complete their tasks with reasonable assurance that the requirements would not change. This turned out to be true for the most part. The significant event affecting this was the February 1967, fire on the launch pad and the tragic loss of three astronauts. More stringent specifications of fire resistance in the cabin's pure oxygen atmosphere turned out to be reasonably straightforward to meet for the guidance equipment.

Except for this, the hardware design remained relatively stable after 1965. This year 1965, however, was the peak year of hardware activity in which almost 600 man years of effort on guidance hardware was expended at MIT out of an MIT total for the hardware part of the program of approximately 2,000 man years. Hardware problems did arise after 1965 but it usually turned out that the expense in dollars and time in solving them by redesign could be avoided by putting the burden of adapting to the problem on the computer program software. This was also true of hardware problems in other parts of the spacecraft.

Software Design

Adapting to hardware problems was only one of the many things which made generating the computer program software difficult. The primary complication was that the details of the mission continually changed and indeed were difficult to get defined in the first place. Then too, so many different programs were needed—different programs for the Block I and Block II computer, different programs for the unmanned and manned flights, different programs for the earth orbital and lunar missions, and different programs for the Command Module computer and the Lunar Module computer.

The effort needed for the software turned out to be grossly underestimated. Until the first lunar landing in 1969, approximately 1,400 man years of effort at MIT was applied to the task. The peak activity occurred one year earlier in 1968 with a manpower total of 350.

Parts of the computer programming were accomplished early and were essentially independent of mission objectives. These included the basic code for the computer executive system, sequence control, timing and interrupt structions, unchanged since originally designed by Dr. Laning, and the management of the interfaces with the computer display and keyboard unit, telemetry, etc. Also completed relatively early were the complex but not time-critical data processing routines of navigation, guidance targeting, trajectory extrapolation and lunar ephemeris calculations. Much of the analytical and algorithmic foundation €or these came from Battin's earlier work for the unmanned space mission studies. For Apollo, Dr. Battin, Dr. James Miller, and Norman Sears, and other analysts made significant improvements in the efficiency and performance of these routines, many of which were of fundamental significance.

The digital autopilots, guidance steering, and other mission specific functions operating during the more stressful parts of the flights required considerable coordination with external agencies — the spacecraft designers, the Manned Spacecraft Center, and the astronauts. Several formal data exchange procedures were attempted, but the most effective in many cases were the direct personal contacts the individual analysts and programmers established with others who they learned had the accurate information.

The computer program requirements were recorded for each mission by the Instrumentation Laboratory in a multivolume document called the "Guidance System Operating Plan" developed initially by John Dahlen and James Nevins. However, the often tardy publication of these plans made them more of a report of what was in the code rather than a specification of what should be coded. The individual programmers also generally drew their detailed flowcharts after the code was written. Standard format flowcharts were generated manually by a large special documentation team.

The very early programs for the first few unmanned earth orbital test flights were each put together by a small dedicated group led by a chief engineer-programmer. For the first command module flight, Alex Kosmala spent many weeks of long hours leading the design and coding of program CORONA. Similarly, Daniel Lickly's great personal effort produced the program SOLARIUM. Each of these was an amazing tour-de-force which was impractical for the more complex manned missions. Each of these later missions was assigned the responsibility of a senior engineer who assumed a more technical management role for the program. The task first was to partition the job suitably for the analysts, specification writers, programmers, test engineers, and documentation specialists. The leader established schedules and progress milestones, reassigned resources to solve inevitable problems, and generally was responsible for the quality of the program. Names notable here are Dr. James Miller for the first Lunar Module program SUNBURST, Dr. Frederic Martin for the Command Module program COLOSSUS, and George Cherry for the Lunar Module program LUMINARY, These last two were the programs used for the lunar landing missions. Martin and Cherry also did a substantial part of the design of the powered flight guidance steering functions for these programs. Alan Klumpp made major contributions to the landing program in the Lunar Module. Daniel Lickly established the atmospheric entry design for the Command Module.

Much of the detailed code of these programs was written by a team of specialists led by Margaret Hamilton. The task assignments to these individuals included, in addition to writing the code, the testing to certify that the program element met requirements. Overall testing of the assembled collection of program elements necessarily took the use of considerable human and machine resources. The programs had to be as near error-free as possible and any anomalies had to be understood and recorded for possible affect on the mission. Actually, no program errors were ever uncovered during the missions.

The highest level of testing was performed with a high fidelity digital simulation of the computer, spacecraft hardware, and mission environment. The creation, development, and maintenance of this simulator by Dr. Miller, Keith Glick, Lance Drane, and others included many diagnostic features essential to its effective use. Testing of the programs with the real hardware was done by Ain Laats in his systems test lab. Wide bandwidth aspects of the program were evaluated in a digital/analog hybrid simulator assembled by Phillip Felleman and

Thomas Fitzgibbon. This hybrid simulator was also arranged to operate with the displays and controls of a pair of cockpit simulators to exercise crew functions in operating the Command Module and Lunar Module. These cockpit simulators were the responsibility of James Nevins assisted Richard Metzinger, Ivan Johnson, and others. The ill-fated crew who died in the fire used this command module simulator in Cambridge for their training of what would have been the first manned Apollo flight. The use of the Cambridge facility was necessary because neither of the mission simulators at Houston or Cape Kennedy was ready.

The content of the flight computer software very clearly determined specific capabilities and procedures in conducting the Apollo mission. As stated earlier, the original philosophy underlying the guidance design was onboard self sufficiency of the astronauts in managing their mission. Early software was written with this crew-directed autonomy in mind, although it was based only intuitively on exactly how the crew would perform their tasks. The issue became clearer as the astronauts participated in the hardware and software design decisions and particularly on mockup and simulator evaluations and the experience being gained in Gemini flights. Initially the flight crew changed the software specifications so that they would participate step by step in the computer decisions during the mission phases. This necessarily made a heavy workload for the astronaut at the computer display and controls. As they gained more familiarity with the system and more confidence in it, the philosophy was modified to allow the computer to flow through the normal mission logic without the necessity for authorizing keystrokes from the operator. However, the astronauts could watch, interrupt, and modify the functional flow if they so chose.

Another decision from the crew resulted in reconfiguring details of the trajectories to be flown so that they could better monitor their progress and, if a failure occurred, they would be in an easier situation from which to take over with backup hardware and procedures. For example, the Lunar Module guidance was easily capable of injecting the vehicle on the ascent from the moon's surface onto a trajectory which would go directly to a rendezvous with the command module. However, the actual procedure used involved a number of more simple maneuvers called the concentric flight plan which had been used in Gemini rendezvous exercises.

Gemini was flown for the last time late in 1966, and the attention of the astronauts and the ground controllers was put fully onto Apollo.

By this time, however, the computer programs were already straining the memory capacity. The Flight Operations Division under Howard W. Tindall at Houston in March 1966, had taken over the management of the MIT software contract. One of Tindall's first actions was to hold a computer memory storage meeting with all involved parties to decide what computer capabilities should be in the limited program space. This occurred on Friday the 13th of May and was thereby nicknamed "black Friday" by those whose favorite program elements were eliminated. Two more black Friday meetings were required and several "tiger teams" were assigned to keep the computer program within its bounds. An outcome was that some programs were eliminated that had provided the complete on-board self-sufficiency. The ground tracking facility and the Mission Control at Houston would be able to perform these functions and would, furthermore, relieve the astronauts of some of their work burden. Enough was left in the on-board computer programs, however, for the crew to rescue themselves and return to earth in case communications were lost.

The management of the software effort, assigned at the time to Edward Copps, necessarily became far more structured. Tindall, supported by others from the Manned Spacecraft Center, held monthly Software Development Plan Meetings in Cambridge to watch progress and the allocation of resources to software tasks. After the programs were essentially complete but still subject to revisions, these meetings changed character to that of a Software Control Board held often-times in Houston. Even after that part of the code in the fixed memory for a given spacecraft was released for manufacture, desired program changes were identified. The logical similarity of fixed and erasable memory and the flexibility of executive and software designs did allow the prelaunch or in-flight loading of special programs into the erasable memory. This was done only under strict authorization of Tindall's software control board. Many of these so-called erasable programs were used inflight to handle miscellaneous problems.

During the later part of this period, Tindall also conducted in Houston what were called Data Priority meetings. These were held to establish the specific trajectory characteristics, operating timelines, and the interacting ground control and astronaut procedures under all normal and unusual conditions. The guidance hardware and particularly the computer programs in the memory influenced strongly the specific paths possible in conducting the mission. Accordingly the task was put onto Malcolm Johnston, at MIT, to search out the needed detailed design data available from the enginesrs in Cambridge for the Data Priority activity in Houston. It was the product of these meetings that finally tied together all mission operations with the guidance, navigation, and control.

Crew training in these operations on the mission simulators required the detailed guidance system instructions provided tirelessly by Russell Larson working with the astronauts at Houston and Cape Kennedy.

Flight Experience

The flight experience of the Apollo guidance system shows a remarkable consistency with expectation punctuated with outright surprises.

The understanding of these surprises and recommending appropriate courses of action fell to a large part on the Instrumentation Laboratory teams in place at Houston, Cape Kennedy, and Cambridge providing guidance system mission support. During the quiet times of the flights, only about four Lab engineers would be on duty, but the number rose at times to several dozen performing special analyses, lab tests, and simulations. Leaders of this activity were Philip Felleman, Russell Larson, and Stephen Copps.

The first mission carrying the guidance system was Apollo 3, which flew in August 1966. It was an unmanned, high energy, suborbital trajectory with **four** separate guidance controlled burns of the Service Module propulsion rocket. These were arranged such that the Command Module would enter the atmosphere with about 20% more specific energy than that in normal returns from the lunar missions. This was planned in order to stress test the reentry heat shield. The landing east of Wake Island about *350* kilometers short of the intended target was due to an unanticipated error in the aerodynamic model of the Command Module. The actual lift available was enough lower than design intent *so* that even though the guidance commanded full upwards lift, the vehicle dropped into the ocean early, The guidance indicated splash point was within 18 kilometers of the Navy's reported retrieval point — this after an hour and a half of uncorrected all inertial navigation through high acceleration maneuvers.

Apollo 4, November 1967, also unmanned was guided into a high apogee trajectory after two earth orbits and was to be given an extra rocket burn on the way down to simualte the lunar return velocity. However, in this automatic maneuver, a ground controller in Australia, confused by a delay in telemetry, sent an engine turn-on signal from the ground just after it had already been initiated automatically by the guidance system. This action transferred rocket cutoff responsibility away from the onboard system. The ground controller sent the cutoff signal 13.5 seconds later than required for the planned entry test conditions. It was, therefore, a severe entry test for both the heat shield and the guidance system. The latter controlled the entry into a range stretching skip out of the atmosphere and a reentry back into it with a splash in the ocean 3.5 kilometers different from the point intended as indicated by extrapolated ground tracking data.

Apollo 5, in earth orbit in January of 1968, was the only unmanned test with the Lunar Module. The mission went as planned until the time of the first guidance controlled Lunar Module rocket burn. The system initiated ignition as planned and using the approved model for thrust buildup looked for the acceleration to rise as expected. A change in the rocket pressurization, not recognized by the software, delayed the thrust buildup longer than accepted by a safety criterion built into the computer program. The system, as designed, then immediately signalled shutoff. As a result, since the problem was not immediately understood, the remaining rocket burns were controlled by a simple backup system. All primary mission objectives were met.

Apollo 6 in April 1968, had a mission similar to Apollo 4, but unfortunately the Saturn booster third stage could not be restarted for the lunar trajectory injection simulation burn. Consequently, the spacecraft Service Module was used for this under guidance system control. Since the resulting burn was necessarily very long as targeted, too little fuel for the maneuver needed to drive the spacecraft back into the atmosphere at lunar return velocity was left. The lower velocity was not enough specific energy for the guidance to steer the vehicle's lift to the planned target, and it fell short by almost 100 kilometers with the guidance indicating a splash within 4 kilometers of that later reported by the recovery force.

The first manned flight, Apollo 7, October 1967, exercised a rendezvous with the spent third stage of the Saturn booster from about 100 miles separation. The sextant was used by astronaut Don Eisele to give the computer direction information referenced to the stellar aligned inertial system. No ranging data were available as the equipment was not yet available. Nevertheless, the computer converged upon a good rendezvous solution. Three times during the flight untested procedures used by the crew caused the computer to "restart" successfully. Restart was a software feature provided in all problems to protect against data loss and provide instant recovery from logically improper activity. Many times in future flights, restart accommodated safety to computer logic and operational problems.

Apollo 8 with the first men to orbit the moon, December 1968, was a fantastic success of man and machine. All of the guidance features in the Command Module were exercised with few problems. In the very first application of on-board autonomous navigation in space, Jim Lovell made over 200 sextant sightings on the way out to the moon. His computer solution of the nearest approach to the backside of the moon agreed within 2.5 kilometers of that later reconstructed from ground tracking data. The critical return-to-earth maneuver, Christmas morning, was so accurate that only a single 1.5 meter/sec midcourse maneuver was required 5 hours later. Lovell's transearth navigation with the sextant indicated approach to the entry corrider within 30% of the normal tolerance. By this he showed that he could have returned safely without the help of the ground control. At one point early in the return, Lovell, thinking he was telling the computer that he was using star number 01, actually punched in the command for the computer to go to the earth prelaunch program 01. This caused all sorts of mischief including the loss of the inertial system alignment. He had no problem getting all this quickly and properly rearranged.

Apollo 9, which flew a very complex mission in March 1969, exercised almost all functions of the Lunar Module guidance in earth orbit including the rendezvous with the Command Module. The only inflight guidance hardware failure in the program occurred early in the mission. A tiny pin got dislodged from the scanning telescope angle counter display rendering the counter useless. The counter, however, was only a backup to the normal readout of the computer display, so fortunately the problem had no impact on the mission. At one point, Dave Scott loaded the celestial coordinates of Jupiter into the computer and asked it to point the optics at the planet. He was rewarded with a fine display of Jupiter and her moons in the 28 power instrument. Later, he loaded the computer with the orbital parameters of the Lunar Module which had by then been abandoned and sent away into a high orbit. There it was in the eyepiece 5,000 kilometers away.

Apollo 10 in May 1969, was a complete lunar mission, except the actual touchdown on the moon was by-passed as planned. All guidance functions were uneventful except that a new technique was developed during the flight to put the vehicle into a stable rotation of 3 revolutions per hour during the long coast to the moon. This spin was used earlier in Apollo 8 to keep the thermal loads on the skin from the sun equalized, but on that mission occasional firings of the attitude jets were necessary to hold the spin as required. Besides wasting fuel, the noise of these firings disturbed the crew's sleep. During Apollo 10, Joseph Turnbull, in Cambridge, exercised various methods on a simulator for initiating the spin *so* that the residual fluid motions in all the fuel tanks would not later on destabilize the spacecraft motions. His procedures were radioed to the crew via Mission Control in Houston; on the second try it worked and stability was achieved without further thruster activity.

Finally on July 20 and 21, 1969, Apollo astronauts first walked on the "magnificent desolation" of the moon's surface. The actual landing was particularly exciting, however, due to alarms in the computer during the descent. These alarms were caused by an erroneous mode switch position resulting in maximum pulse rate signals being sent to the computer from the rendezvous radar, which was, of course, not needed during the landing. The computer, already operating near capacity, was overloaded by these extraneous inputs causing it to restart and display the alarms. The ground controllers and Neil Armstrong were on top of the problem. They knew well that the computer, in restarting, would keep the essential programs running for the landing. However, Armstrong's attention was diverted during the time he should have been using the window display which would indicate to him what the lunar surface was like at the point where the guidance system was bringing him. When he finally looked, it was a young ray crater strewn with large rocks. It was too late to retarget the computer for the more efficient trajectory change to a more suitable point. Instead, he selected a semiautomatic altitude hold mode and maneuvered across the crater to a landing at "Tranquility Base".

Apollo 12 in November 1969, was hit by two lightning strikes early in the boost to earth orbit. The large current pulses, passing through the innards of the command module surrounded by the insulating heat shield, caused power transients which forced the computer to restart both times. Although the computer did not lose any memory, the interface circuits to the inertial system were affected transiently and Pete Conrad reported a tumbling inertial platform. Fortunately, the Saturn booster guidance system, further distant from the current pulse, was not disturbed and completed its normal function. The crew was able to realign the inertial system to the stars while in earth orbit, and continue the mission. They landed on the moon on the edge of the small crater in which had sat the unmanned Surveyor spacecraft since its arrival two and a half years earlier.

The emergency and rescue of the Apollo 13 crew in April 1970, after the explosion and loss of oxygen and power in the Service Module, urgently depended upon a quick maneuver to get back on an earth's return trajectory using the only propulsion available, that of the Lunar Module. The Lunar Module autopilot was not designed to push the heavy Command and Service Module through the limber docking joint as a normal control mode. However, for just a contingency such as this, the necessary software had been developed by the Instrumentation Laboratory and was included in the computer program; but it was very little tested. The critical maneuver was accomplished with stable control. Without Service Module power and in order to conserve the limited life Command Module batteries for the entry, the guidance system there was shutdown completely. After three days of cold, rough treatment for the precision instrument, would the inertial system get reheated without harm, get started and aligned, and retain its calibration for it use in guiding entry? The entry proceeded normally and splash in the ocean was indicated within one kilometer of the target.

The February 1971 mission of Apollo 14 was normal for the guidance system until about three and a half hours before the scheduled powered descent onto the moon. At this time the Lunar Module computer started receiving intermittent faulty signals from the main panel abort button, which, if they occurred during the descent to the moon, would irrevocably start the abort sequence sending the vehicle back into orbit. As in every mission, the Instrumentation Laboratory* support engineers in Houston, Cape Kennedy, and Cambridge were monitoring progress and immediately started working on a way of preventing the mission from being terminated needlessly. Among the various ideas proposed, one suggested by a young engineer, Donald Eyles, was selected and after hurriedly being tested on the simulators in Cambridge was sent over the circuits to the Mission Control Center in Houston for their evaluation. This procedure, which was sent up to the crew as soon as they came around from the back of the moon, involved four sets of computer input keystrokes to be made onboard at appropriate times in the descent. The First of these would fool the necessary part of the computer logic into thinking that is was

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* Actually, a year earlier, the Instrumentation Laboratory had been renamed The Charles Stark Draper Laboratory in honor of its founder.

already in an abort mode while the landing programs, nevertheless, would continue to bring the vehicle down to the lunar surface. The astronauts had only 10 minutes after receiving this computer reprogramming procedure before they had to start their descent. They accepted it: and the landing went flawlessly, exactly to the planned spot on the moon.

There were three more lunar landing missions, three earth orbital visits to the Skylab, and the rendezvous with the Soviet cosmonauts in Soyuz. Although the Apollo guidance, navigation, and control system contined to get involved in the unexpected, any further account would be anticlimactic to the dramatic saving of the Apollo 14 and its objective—the landing of men on the moon.

Comment

This account is written from the point of view of one who experienced the hectic but exciting years. The intent was to underline significant events and ever-changing design emphasis and to support this with limited anecdotal items and reminiscences. An enormous amount of material has been left out for practical reasons, and many worthy names regretfully remain unmentioned. Technical details have been deliberately played down: they can be found in the bibliography. The overall message is simple: In an incredible and audacious task, the landing of men on the moon, the guidance equipment for the mission was created out of primative principles, prolific imagination, and a lot of hard work.

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