THE EVOLUTION OF FLIGHT CONTROL OF THE APOLLO MISSION

Dr. Maxime A. Faget*

The purpose of this paper is to recount how the various Apollo flight control techniques and systems were first conceived and how they evolved. However, as I started tracing early events and attempted to recall to memory the motivation for the things we did and didn't do, it became increasingly clear that the question at the time was not how man may fly to the Moon, but could it be done with adequate safety. And one of the dominant considerations concerned the feasibility of navigation and flight control. Thus, the evolution of flight control of the Apollo mission is best seen as part of the history of American manned space flight.

Shortly after NASA started the Mercury Program to make experimental orbital flights of a man-carrying spacecraft it also started considering more ambitious manned space missions. Although the Mercury team, called the Space Task Group, was the focal point for most of this planning, virtually every NASA installation was involved in some sort of advanced mission study involving manned space flight. Furthermore, the USAF, the Army's ABMA and a number of industrial teams were also promoting or participating in this sort of activity. In the Spring of 1959 NASA formed a Research Steering Committee on Manned Space Flight. This committee became NASA's first forum for coordinating the various planning studies then underway. The most obvious and appealing prospect was for some type of lunar mission. Three types of manned missions were considered. They were in order of increasing difficulty, circumlunar flight, lunar orbit, and lunar landing. Our initial considerations for these missions in retrospect may appear quite naive. However, they were based on a very narrow experience base and a conservative assessment of technology. Although the Mercury mission of manned orbital flight had not yet been achieved, the basic approach had been firmly set, and hardware development was sufficiently mature to demonstrate that we were on the path to success. The Mercury design and flight operation philosophy had a dominant influence on lunar planning.

Compared to flying to the Moon and back, the Mercury Program requirement of orbital flight could be met by relatively crude flight control hardware. Basically the Mercury spacecraft was to be inserted into a low earth orbit using the launch vehicle guidance system. Once in orbit, no further velocity change maneuvers were required until it was time for descent. Return to earth was accomplished by firing a cluster of three solid rockets. This deflected the flight path to one which entered the earth's atmosphere. Since the spacecraft was designed to produce no lift, it followed a highly predictable ballistic entry trajectory. Consequently, the time at which the retro-rockets were fired primarily determined the location of splash down in the ocean. It was recognized that there would be a fairly large dispersion about the planned landing location. However, consideration for emergency descent or aborts during launch which could result in a landing anywhere along the flight track made survival for a period of time on the water after landing and extensive use of location aids a basic design requirement anyway.

---

*Dr. Faget is Director of Engineering and Development, NASA-Johnson Space Center, Houston, Texas

Flight control equipment onboard the spacecraft was needed only for attitude control and firing the retro-rockets.These functions could be done both manually and automatically. When in automatic flight an autopilot and a horizon scanner were set up to maintain the vehicle in a fixed attitude with respect to local vertical, there was also a timer onboard which initiated the retro firing sequence after commanding the attitude to the optimum one for the maneuver. This timer which was started at lift-off could be corrected during the flight by command signals from the ground. The astronaut could also control attitude with a hand controller using either an attitude indicator on the instrument panel or by looking through the window. He could also override the automatic initiation of the retro-rocket sequence. The astronaut could crudely determine his position in orbit by comparing his view of the earth with a clock driven replica of the earth's globe.

The control of the mission was carried out on the ground. Communications with the spacecraft and tracking data were obtained from a network of stations along the path of the first three orbits. There were 16 different stations so located to allow a maximum of 10 minutes without communication contact. The data from these stations was sent to the Mercury Control Center at the launch site in Florida. It was on the basis of this processed tracking data that orbital ephemeris was determined. The location of intended splashdown was predetermined to accommodate post retro-firing tracking, thereby enhancing final location for recovery.

Since it required the least amount of propulsion, the least sophistication in navigation and guidance equipment onboard the spacecraft, and it clearly seemed the least hazardous, the first mission seriously considered for manned lunar flight was simple circumlunar navigation and return. This seemed to be modest extension of orbital flight - in fact, circumlunar flight is achievable by a highly eccentric earth orbit of the proper parameters. However, the gravity field of the Moon creates a major influence on such orbits. Consequently, even the smallest error in state vector at the time of translunar injection could not go uncorrected if a safe entry into the earth's atmosphere was to be made at the end of the mission. It was clear that flight path corrections would have to be made. The question was how to determine the error and how accurately could the corrections be made.

There was real concern by a number of NASA leaders, particularly Dr. Harry Goett, Chairman of the NASA Research Steering Committee on Manned Space Flight, that a safe entry into the earth's atmosphere at lunar return velocity might be beyond the guidance and navigation "state-of-the-art" technology. At these velocities, during the initial stages of entry, the spacecraft must pull negative lift to skim along a very narrow corridor of the upper layer of the earth's atmosphere. If the upper boundary of this corridor were exceeded, the spacecraft would skip out of the atmosphere back into a highly eccentric orbit and perhaps expend its supplies before re-entering the atmosphere a second time. On the other hand, if the corridor boundaries were missed on the lower side, the spacecraft would exceed the heating or load limitations of its structure. An associated concern was entry and landing point location. Since the mission was not very well understood, it was conjectured that the time of return might vary greatly from the planned time, and because of the earth's rotation the geographical position of the entry may have a large dispersion. For these reasons configurations with a fairly high lift-to-drag ratio appeared desirable. In summary, the thinking in 1959 was that from a flight control.standpoint the circumlunar mission would be flown using ground-based navigation obtained from tracking data. Guidance instructions would be transmitted to the crew for the necessary mid-course corrections. A budget for velocity changes as high as 500 ft/sec., was initially estimated for this purpose. Tracking and communications would be maintained to the entry interface. The entry guidance would be done with an inertial measuring system and an onboard computer that would receive a navigation update prior to entry. The aerodynamic configuration of the entry vehicle was estimated by some to need a lift-to-drag ratio of better than one to provide a large maneuvering footprint while safely staying within the entry corridors.

Concurrent to this activity the Deep Space Information Facility (DSIF) was being defined by JPL. This would consist of three communication and tracking stations located at approximately 120 degree intervals around the earth, and thus could continuously track and communicate with any spacecraft on a lunar or interplanetary mission. This development subsequently led to the Manned Space Flight Network (MSFN) which was used to support all the Apollo missions. This consisted of three 85' diameter antennas dedicated to the Apollo program but located at the same sites as the DSIF. I will come back to the use of MSFN later.

During 1960 enough studies had been carried out by NASA and industry to achieve a fairly good understanding of the implications of various manned lunar missions. Lunar orbit missions with a total flight duration of 2 weeks received a great deal of interest. Such a mission did not appear to be a great deal more difficult than circumlunar flight, but would provide much more scientific data. Furthermore, it would provide the means of gaining significant flight operational experience and reconnaissance data that would support a future lunar landing. The biggest hindrance to enthusiastic support for lunar landing was the enormous size of launch vehicle that would be required. Another consideration was that features of the lunar surface were known to a resolution of no better than one kilometer. Thus, the roughness and soil properties of the surface upon which a landing would have to be made were woefully unpredictable.

Meanwhile NASA had moved out with an unmanned space flight program to explore the planets of the Moon. The Ranger spacecraft was a probe that transmitted a few closeup images of the lunar surface just before colliding with the Moon at high velocity. The Surveyor was a soft-lander that made five successful landings on the lunar surface. Subsequent to landing, the Surveyor transmitted pictures of the surrounding features of the moonscape providing extremely useful information on surface roughness as well as the quantity and size of rocks. Just as important, engineering data obtained from the Surveyor landings were extremely valuable in verifying the firmness of the lunar surface for the landing of the Lunar Module. The unmanned Lunar Orbiter flights, however, were every bit as valuable to the Apollo Program. They provided high resolution photographs of the lunar surface that were extremely useful in selection of landing sites. The cartographic quality of the photographs was more than sufficient to make accurate maps of the lunar surface that could be used for orbital navigation and for visual recognition by the astronauts in the terminal phase of their descent. Just as important, analysis of orbital tracking data greatly improved the accuracy of the lunar gravitational constant and provided valuable data on lunar gravitational anomalies - all of which facilitated translunar and lunar orbit navigation on the first missions.

Before any of these unmanned missions had been successfully accomplished, our concern with the suitability of the lunar soil to support the Lunar Module led us into a study of the use of penetrometers for this purpose. The concept was that a number of penetrometers would be carried aboard the Apollo. The Apollo would be put in an orbit that would pass over the chosen landing site a number of times. One or more penetrometers would be released, whereupon most of their forward velocity would be checked by a retro-rocket. Upon hitting the surface, the penetrometers would telemeter a deceleration signature that could discriminate the suitability of the soil to support the Lunar Module upon landing. Happily, information obtained by the successful landing of the Surveyors eliminated the need for these penetrometers.

There was also great concern with the accuracy of navigation in lunar orbit and that the landing might be made in an unexpected and unsuitable location, for instance, on a rugged mountain slope rather than a smooth plain or valley. Since the radius of the Moon is comparatively small and because the surface features are quite rugged, the astronauts would be completely committed to the general area of the landing before it came within view. For this reason it seemed highly desirable to have a radar beacon at a known location relative to the landing site as a terminal navigation aid. Like the bell on the cat, this was considered a wonderful thing without a practical means of accomplishment. Design studies were made of beacon-carrying hard-landers that could be deployed from the Apollo spacecraft near the desired landing location. Fortunately, the cartographic maps and knowledge of the gravitational figure of the Moon resulting from the Orbiter missions coupled with confidence in improved navigation techniques terminated this work before too much effort was wasted. In fact, the accuracy of navigation techniques that were ultimately developed made it possible for Apollo 12, the second landing mission, to come to rest within short walking distance of Surveyor III that had landed on the Moon two and one-half years previously. The Surveyor's location had been identified on a Lunar Orbiter photograph by patient and meticulous study.

I would like to go back again to 1960 when the concept of the mission itself was still being established. We at the Space Task Group visualized that, regardless of the ultimate goal, the first flight would be circumlunar with the spacecraft passing within several hundred kilometers of the lunar backside. After this, orbital flights would be made using the same outbound and homeward navigation techniques proven in the circumlunar missions. Finally, a lunar landing would be made by descending from lunar orbit. By this scheme of things each mission would be an extension of the previous one, thus, the overall difficulty of achieving the final goal would be divided into a number of incremental steps, each with a greatly reduced exposure into the unknown. Nevertheless, the first time a plan to make a manned landing by descending from lunar orbit was outlined to NASA management, several in the audience severely questioned the wisdom of not taking advantage of the experience that would be obtained from Surveyor, which was designed to go directly from the earth straight down to the lunar surface. Clearly, they had not considered how thrilled the crew would be during a landing that started at hyperbolic speed in a near vertical direction and would be fully committed before they knew if the landing propulsion would fire up. I only mentioned this incident to illustrate that at the same time that a manned lunar landing was seriously debated, the basic understanding of the venture was still quite primitive.

As conceptual mission plans firmed up it became clear that both lunar orbit and lunar landing would require sophisticated onboard navigation and guidance capabilities. It was not considered feasibile to provide this function from the ground. The Instrumentation Laboratory at MIT had been studying both lunar and Mars missions for some time and had established themselves as the leaders in deep space navigation. A contract was therefore negotiated with MIT making the instrumentation Laboratory a partner to the Space Task Group in studying manned lunar missions. Subsequently, when the Apollo program was implemented, the

Instrumentation Laboratory became the program's first contractor when they were given the responsibility for the onboard navigation and guidance hardware which subsequently included the digital autopilot. Dr. Hoag's paper presents a historical account of these and related systems.

The Apollo Program got its official blessing and start when on May 25, 1961, President Kennedy said "....I believe that this Nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the earth." This precipitated a great number of decisions. The guidance and control precision for atmospheric entry at lunar return velocity was sufficiently well established to commit to an entry configuration that would have an L/D of 0.5 instead of a value of one previously mentioned. The selected 0.5 L/D value was compatible with the use of a semi-ballistic entry configuration design. Such configurations could achieve the relatively low entry heating of high drag ballistic designs with a modest amount of lift. Furthermore, these features could be embodied in an axisymetrical shape which simplified a number of design, manufacturing and test considerations. The design chosen for Apollo was a derivative of the Mercury shape. By offsetting the center of mass a distance of 7½ inches from the center line, Apollo would trim at about 33 degree angle of attack which was sufficient to produce the desired L/D of 0.5. With this much lift Apollo could be confidently guided to land 5000 miles downrange of the entry interface.(1) On the other hand, the landing point could be limited to only 800 miles downrange without exceeding 4 g's deceleration. However, an interesting thing happened between preliminary design and final assembly. As various equipment was stuffed in the entry capsule, the center of mass inexorably moved toward what one of our engineers called the "idiot point." That is the center of volume. Consequently, the center of mass ended up displaced only a little over 5 inches from the center line and the resulting L/D was 0.35. However, this was more than sufficient. Planned splashdown for all missions actually flown was set for 1400 miles downrange with the never used capability to either decrease it to 800 miles or increase to 2200. I should mention here that only once in all the returns from the Moon was it felt desirable to move the pre-planned landing point. It was moved 500 miles further downrange to avoid the possibility of predicted bad weather at the initially intended landing point. However, the decision to relocate was made early, and the change was accomplished by a propulsive maneuver during transearth coast a day prior to entry. Thus, the actual flight was a standard one with the nominal downrange distance.

Returning once again to 1961, the decision by President Kennedy to make a lunar landing the principal space effort of the decade precipitated the famous debate on the mission scheme to be employed. NASA, industry and the USAF at that time were studying a great variety of launch vehicles. The most mature of these studies was by the Marshall Space Flight Center dating back to the days when they were still part of the Army. Marshall's principal effort was devoted to the Saturn series of launch vehicles. Dr. Haeussermann is presenting a paper in this session which will recount the history of the development of the Saturn's guidance and navigation system. The NASA also was studying a larger launch vehicle, called the Nova, but this was planned to come after the Saturn.

The lunar landing missions studied by the Space Task Group required a launch vehicle more powerful than the largest Saturn under consideration. This was so since it was at that time envisioned that the entire spacecraft would land on the Moon. Since there was insufficient confidence that a Nova class launch vehicle could be built, attention was turned to employment of rendezvous in lunar orbit or earth orbit as alternatives that would fit the mission within the capability of the largest feasible Saturn class launchers. Without getting into the multitude of considerations that finally settled this sticky situation, lunar orbit rendezvous was chosen. Thus, Apollo became two spacecrafts; the Command and Service Module manufactured by North American, and the Lunar Module manufactured by Grumman.

From a mission planning and guidance and navigation standpoint, lunar orbit rendezvous was completely compatible with all the work that had taken place up to the time of that decision. The requirement of rendezvous in lunar orbit during the mission, of course,had a major impact on onboard equipment and operational techniques associated with rendezvous navigation. More than anyone else, Dr. Gilruth was greatly concerned with the high increase in difficulty that the Apollo missions represented when compared with Mercury. He, therefore, convinced NASA that the Gemini Program was a necessary interim step that would, among other things, provide a means for gaining experience and building up the organization needed for Apollo.

Gemini was extremely valuable as a tool for developing flight control techniques and procedures for orbital rendezvous. Furthermore, the general philosophy of the interplay between the Mission Control Center in Houston and the astronauts in the spacecraft was developed during the Gemini Program. This is particularly true in dealing with the critical problem of mission navigation. Gemini also had its center of mass displaced from the centerline to produce a weak but sufficient amount of lift to control its flight path during entry. The basic scheme used in Apollo of rolling the lift vector about the stability axis to steer the flight during entry was proven in the Gemini Program.

Both the MSFN and hardware onboard Apollo were able to produce highly accurate navigation data. Data from both sources were checked against one another prior to making any velocity change maneuver. Also, immediately after the maneuver was made, data was again cross-checked. Navigation done on the ground had the benefit of a large complex of powerful computers. Furthermore, at least two S-band trackers were always available as data sources. On the other hand, onboard navigation was a necessity in the event communication equipment failed. Ground processed navigation data was transmitted directly to the spacecraft computer. However, as a crew option, it could be held out in a separate register for display prior to insertion into the memory.

The data from the S-band tracker was extremely accurate. In addition to providing a doppler count for velocity, the carrier signal was also phase-modulated with a pseudo-random noise (PRN) code for range measurement. This digital signal which was non-repetitive for 5½ seconds, was turned around and re-transmitted on another carrier by a transponder on the spacecraft. Distance measurements with an accuracy of about 10 meters could be obtained. Velocity measurements were much more useful. High powered data processing techniques could produce an accuracy better than a millimeter per second by smoothing doppler data over a period of one minute. With such data,extremely accurate state vectors could be obtained not only on translunar and transearth flight, but also while Apollo was in lunar orbit. This was extremely important since lunar gravity anomalies and venting from the spacecraft continually perturbed the orbit. Computational techniques were developed to the point where tracking data obtained from the Lunar Module during its landing descent burn could be processed to serve as a sufficiently accurate "tie-breaker" in the event that onboard primary and back-up computations produced inexplicable differences. This highly sophisticated computation technique was developed by Bill Lear of TRW.

The general approach to mission planning was to break the mission down into a number of discrete events and periods. Each of these was analyzed in great detail and a complete model of the mission to great precision was constructed before flight. The missions when flown would usually duplicate the plan to exact detail. A feature of the planning was the inclusion of time allowances for unexpected events so that the preplanned schedule could be maintained. The advantage was that almost every event or phase of the basic mission was extremely well understood and exercised. In addition to the basic mission plan there were a great number of contingency plans that would cover every rational problem.

All missions were planned to accommodate mid-course corrections both outbound and on return. There were specific times set aside for these maneuvers. Outbound there were four times set for mid-course correction events, whereas on the transearth leg there were three. However, if the error to be corrected was sufficiently small, the maneuver would not be made and, as a matter of fact, many missions used only one corrective maneuver each way. When we first started considering translunar flight in 1959, we budgeted 500 ft/sec for mid-course corrections. The estimated need was down to 300 ft/sec when we actually put the program into gear several years later. When we actually started flying the 3σ estimate was 78 ft/sec. As it turned out most flights required less than 20 ft/sec. For example, on the last flight, Apollo 17 executed only one correction maneuver each way: translunar it was 10.6 ft/sec, and for transearth only 2.1 ft/sec was needed.

Optimization of trajectories, improved precision and other sophistications in the guidance, navigation and control systems can greatly reduce the quantity of propellant needed for any space mission. This was particularly true for the Apollo missions where a large number of large velocity change maneuvers were required. A basic planning problem was the quantity of reserve propellant to carry for worst case flight control performance. A particularly bothersome consideration was that secondary or back-up systems usually did not have the precision of the primary system. Consequently, in planning missions expendables, all return maneuvers were usually based on the worst case performance of the poorest system in the redundancy chain. Nevertheless, as successive missions were flown, it was usually found possible to increase the load carry capacity in terms of instruments or returned lunar material without compromising safety. However, the impressive fact is that nine missions were flown to the Moon with almost flawless performance of the guidance, navigation and control systems.

Reference

(1) An arbitrarily chosen altitude (400,000) where atmospheric encounter was presumed to first begin.