

The Apollo Guidance Computer

A Designer's View

Eldon Hall *Designer, Apollo Guidance Computer*

In the early sixties the so called mini-computer had not emerged and there was no commercial computer suitable for use in the Apollo mission. Most of the technologies that were eventually used in the Apollo computer were just emerging from research and development efforts. The design was mainly a task of fitting the components together in order to meet the mission requirements for computational capacity and miniaturization.

From Polaris to Apollo

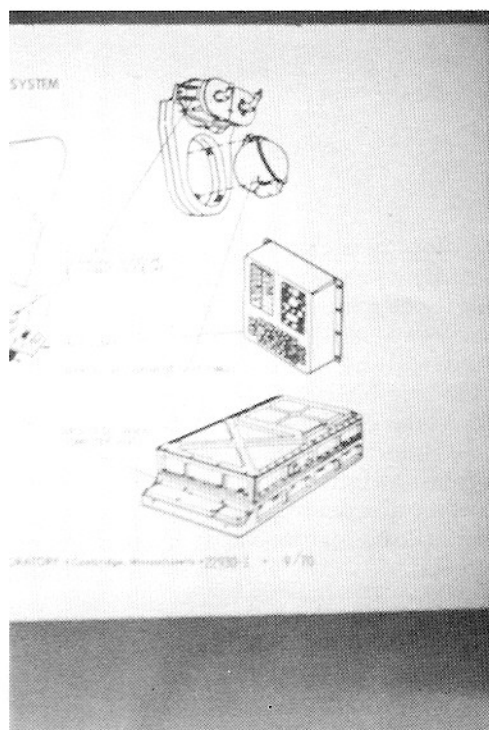
Previous aerospace computers greatly influenced the development of the Apollo Guidance Computer. The demands that were placed on these computers provided the motivation to miniaturize and develop semiconductors. The MIT Instrumentation Lab, now called Charles Stark Draper Laboratory, had the

responsibility for the design of the computers used in the Polaris, Poseidon, and Apollo programs.

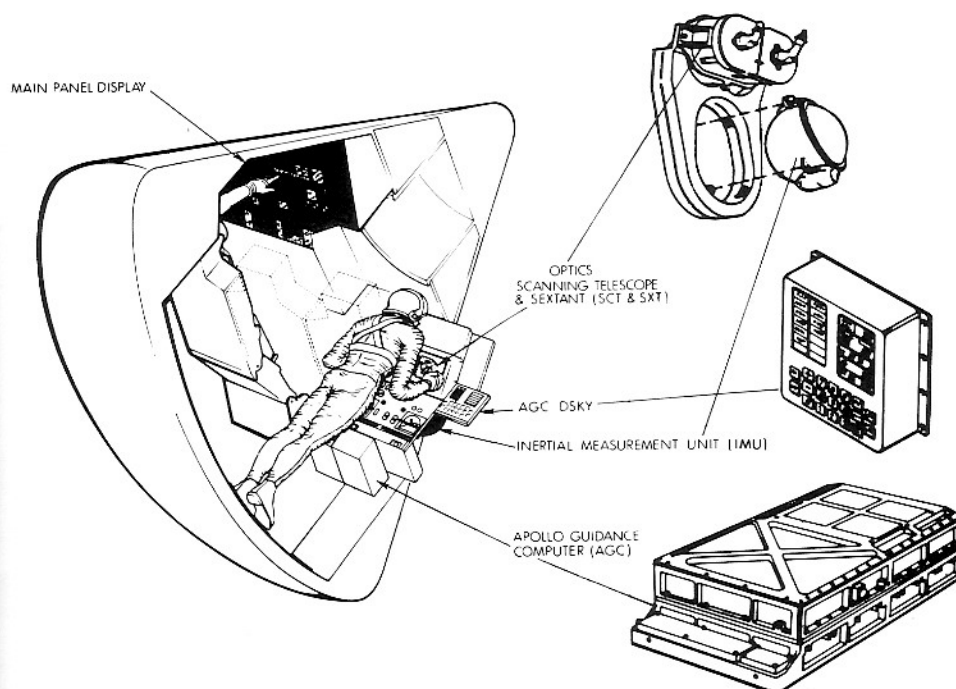
The lab's first significant venture into the field of digital computing was for Polaris, a very small ballistic missile launched from a submarine. A special purpose digital computer was designed to solve the specific equations required for the guidance and control system based on analog techniques originally developed by the Navy. With the need for increased accuracy the Navy decided to use digital techniques for the Polaris program, resulting in the construction of a wired-program special purpose computer to solve the guidance and control equations. In 1959 the first version of this system, called the Mark 1, flew in a Polaris missile. It was the first guided flight of a ballistic missile flown with an on board digital computer providing

the guidance and control computations. The computer occupied about four-tenths of a cubic foot, weighed 26 pounds, and consumed 80 watts. Even before this first guided flight designs were being explored which would reduce the size and improve the maintainability of the system. The new design, eventually designated Mark 2, repeated the architecture and logic design with improvements in circuits and packaging.

In August 1961, when NASA contracted the laboratory to develop the Apollo guidance, navigation, and control system, the mission and its hardware was defined in only very broad terms. A general purpose digital computer would be required to handle the data and computational needs of the spacecraft. Therefore a special arrangement of display and controls would be necessary for in-flight operations.



Eldon Hall pointing to one of the many diagrams shown during his illustrated lecture.



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The boost phase of the mission, which was the Saturn system, had its own internal guidance system to put the command and service module in translunar trajectory. Then the Apollo system took over to guide the mission to the moon.

In effect, navigating in space is the same as navigating on Earth. One might take a star sighting with a sextant. That information is put into the computer and from it the state vector, i.e. the position and velocity of the missile at any point of time, is computed. The computer orients the missile such that the change in velocity will cause the state vector to be updated so the missile will free-fall into the targeted point. While it is thrusting, the guidance system must control the attitude of the vehicle, the magnitude of the thrust in the case of the Lunar Excursion Module (LEM), and the direction of the thrust in the case of the Command and Service module.

Design Constraints

Initially, the need for a very reliable computer with significant computational capacity and speed

was clear. The design constraints included very limited size, weight, and power consumption. If the designers had known then what they learned later, or had a complete set of specifications been available as might be expected in today's environment, they would probably have concluded that there was no solution with the technology of the early sixties.

Establishing interface requirements was a monumental task. The astronaut interface was one of these. In 1962, computers were not considered user friendly. Heated debates arose over the nature of the computer displays. One faction, which usually included the astronauts, argued that meters and dials were necessary. Logically, the pressure for digital displays won most of the arguments because of their greater flexibility in the limited area allowed for a control panel. In late 1963, as the requirements for the LEM were being firmed up, NASA decided to use identical guidance computers in both the command module and the LEM.

In the early manned orbital missions before Apollo, NASA

Major units of the CM Guidance, Navigation and Control System.

learned that the human animal, confined in a spacecraft for a week or so, was not as clean as might be expected from observations on Earth. This additional constraint had a rather interesting and far-reaching impact on the mechanical design of the computers and other hardware. All electrical connections and metallic surfaces had to be corrosive resistant and even though the computer was designed to have pluggable modules, everything had to be hermetically sealed.

The Suppliers

By the end of 1962, NASA selected three contractors: General Motors' AC Sparkplug Division for the inertial systems and system integration; Raytheon, Sudbury Division, for the computer and computer testing equipment; Kollsman Instrument for the optical systems; North American Aviation for the command and service module; and Grumman Aircraft for the Lunar Excursion Module.

In late 1959 and 1960 the lab began evaluating semiconductors, purchased at \$1,000 each from Texas Instruments. Reliability, power consumption, noise generation, and noise susceptibility were the prime subjects of concern in the use of integrated circuits in the AGC. The performance of these units under evaluation was sufficient to justify their exclusive use in place of the core transistor logic proposed initially for the Apollo project design. The micrologic version of the Apollo computer was constructed and tested in mid 1962 to discover the problems that the circuits might exhibit when used in large numbers. Finally, in 1964 Philco-Ford was chosen to supply the integrated circuits used in the proto-

type computer that operated in February 1965. These cost approximately \$25 each.

Specifications

Approximately one cubic foot had been allocated in the command module for the computer. The first prototype was operating in the spring of 1964 and utilized the wire wrap and modular welded cordwood construction which had been produced for the Polaris program. It was designed to have pluggable trays with room for spare trays.

Since the clock in the computer was the prime source of time, it had to be accurate to within a few parts per million. The data and instruction words in the memory were 15 bits plus parity. Data was represented as 14-bit binary words plus the sign bit. Double precision operations were provided to supply 28-bit computations. The instruction word contained the address and operation codes for the computer operation. The memory address field was extended by organizing the memory in banks.

The AGC had 2,000 15-bit words of erasable core memory and started with 12,000 words of read-only memory, called rope memory. It was quickly upgraded to 24,000 words. Then by mid-1964, when

the first mission program requirements had been conceived and documented, there was increasing concern about the possible insufficiency of the memory. This prompted a further expansion to 36,000 words.

Design and Use of the Console

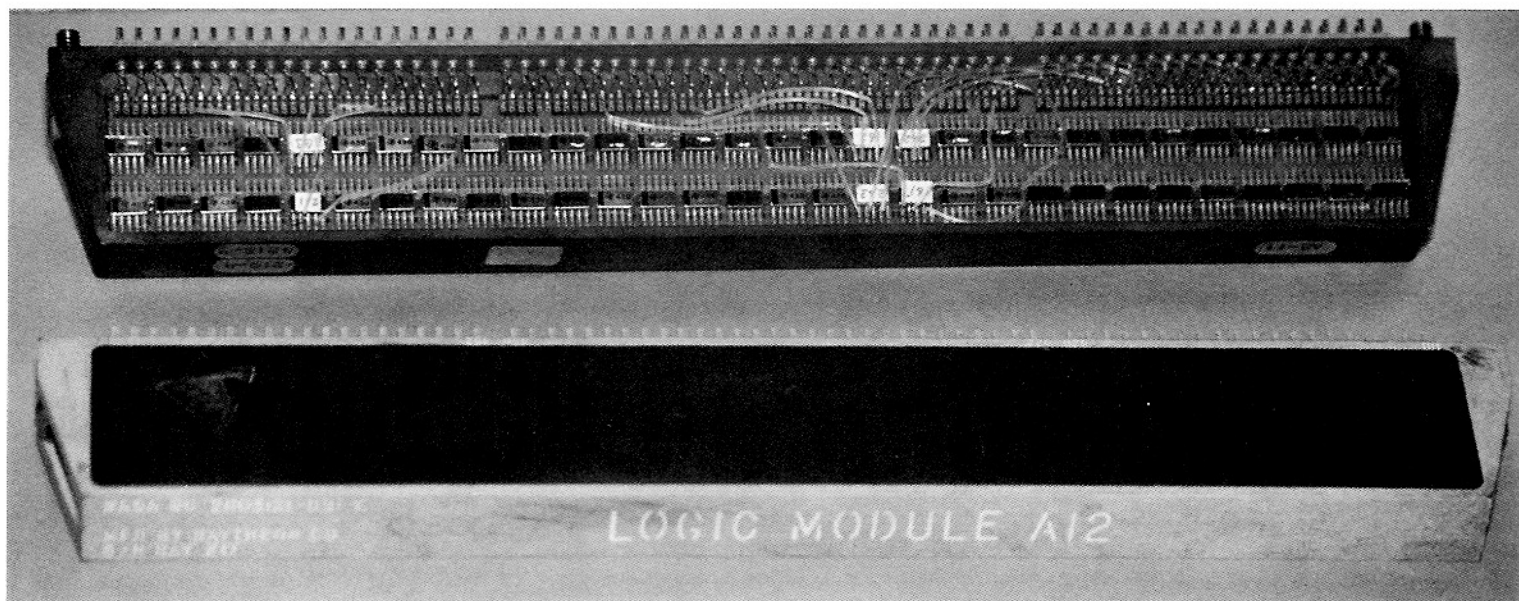
A display and keyboard was developed for the astronauts and had the designation DSKY (pronounced "Diskey"). Functionally, the DSKY was an integral part of the computer, and two were mounted remotely and operated through the discrete interface circuits. One was for a sitting position and another one near the entry to the LEM, convenient for a reclining position.

The principle part of the DSKY display was a set of three numeric light registers. Each register contained 5 decimal digits consisting of segmented electroluminescent lights. Five decimal digits were used so that a computer word of 15 bits could be displayed in either decimal or octal. In addition, three two-digit numeric displays indicated the major program in progress, the verb code and the noun code. The verb/noun format permitted communication in a language whose syntax was similar to that of spoken language. Examples of

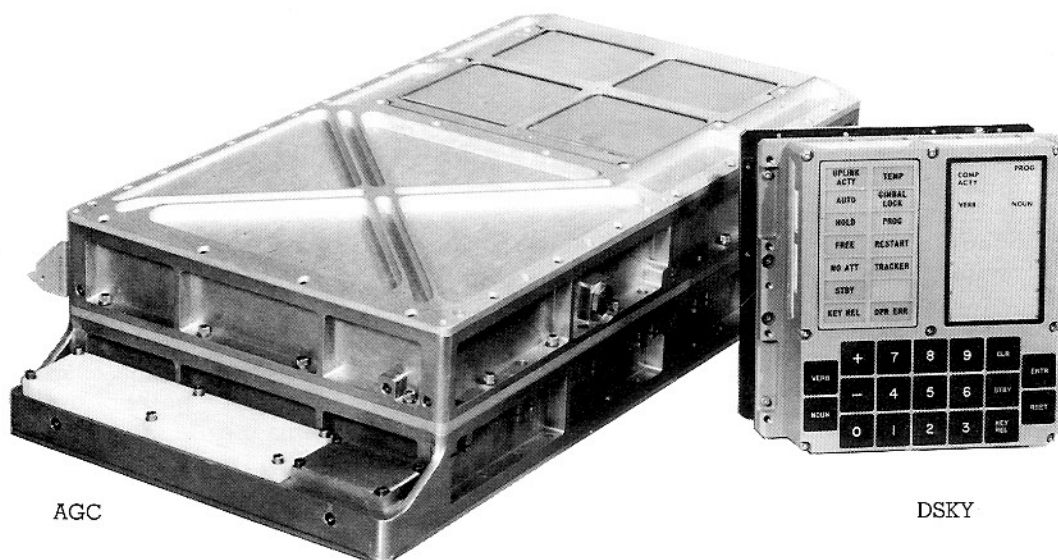
verbs were display, monitor, load, and proceed. Examples of nouns were time, gimbal angles, error indications, and star identifications. Commands and requests were made in a form of sentences, each with a noun and a verb, such as display velocity or load desired angle. To command the computer the operator pressed the Verb key followed by a two digit code. This entered the desired verb into the computer. The operator then pressed the Noun key and a corresponding code. When the enter key was pressed, the computer carried out the operation that had been commanded. The computer requested action from the operator by displaying a verb and noun in flashing lights so as to attract the astronauts' attention.

In-flight Use

Shortly after liftoff of Apollo 12, two lightning bolts struck the spacecraft. The current passed through the command module and induced temporary power failure in the fuel cells supplying power to the AGC. During the incident the voltage fail circuits in the computer detected a series of power trenches and triggered several restarts. The computer withstood these without interruption of the mission programs or loss of data.



The module in the background is exactly the same as one in the foreground, but it has only been used on Earth. The Museum's prototype computer ran at Draper Labs and was used to test the routines for the in-flight machines. In space all of the components had to be totally "potted" to insure that all the parts would stay firmly in place and remain uncontaminated during space flight.



AGC

DSKY

The Apollo Guidance Computer, shown on the left, was responsible for the guidance, navigation, and control computations in the Apollo space program. The AGC was the first computer to use an integrated circuit logic and occupied less than 1 cubic foot of the spacecraft. It stored data in 15 bit words plus a parity bit and had a memory cycle time of 11.7 microseconds, utilizing 2,000 words of erasable core memory and 36,000 words of read-only memory. The frame is made of magnesium for lightness and designed to hermetically seal the components.

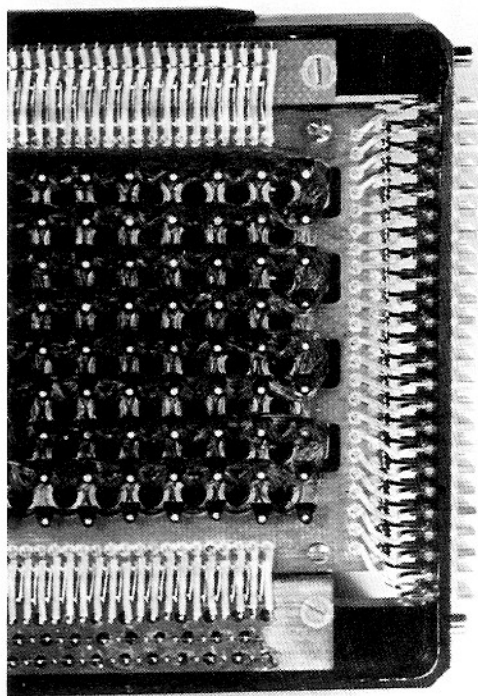
The interface with the astronauts was the DSKY, shown on the right. It used digital displays and communicated with the astronauts using the verb and noun buttons visible in the photograph and two digit operation and operand codes. A set of status and caution lights is shown in the top left corner of the DSKY.

The AGC and DSKY are on display in the Four Generation Gallery.

The AGC rope memory

The read-only memory of the computer consisted of six rope memory modules, each containing 6,000 words of memory. This special type of core memory depended on the patterns set at the time of manufacture. Its sensing wires were woven into a set pattern information. It had five times the density and was far more reliable than the coincident current core memory used for erasable storage in the computer. Being unalterable, it also provided a greater incentive for error-free software development.

The AGC rope memory is on display in the primary memory case.



The Apollo 11 lunar landing had an anomaly which attracted public attention. The computer in the LEM signalled a restart alarm condition several times during a very critical period prior to touchdown. This fact was broadcast to the public and those who knew its significance were close to a state of panic. After analysis, it was determined that the alarms were an indication to the astronauts that the computer was overloaded and was eliminating low priority tasks from the waitlist.

The overload resulted from the rendezvous radar being set in the

wrong mode during the lunar landing phase, wasting computer memory cycles. The computer software was responding to overloads as designed.

This incident triggered a news brief in *Datamation* in October, 1969, faulting the computer design for being too slow. It rightfully claimed that there were a number of minicomputers, including the PDP-11, that were at least an order of magnitude faster. In the eight years since the initiation of the Apollo program commercial technology had far surpassed that of the Apollo design and

capacity. However, no commercial computer could claim to match the power consumption and space characteristics of the AGC.

Excerpted from an Illustrated Lecture, June 10, 1982, by Ben Goldberg. The video-tape is archived by The Computer Museum.