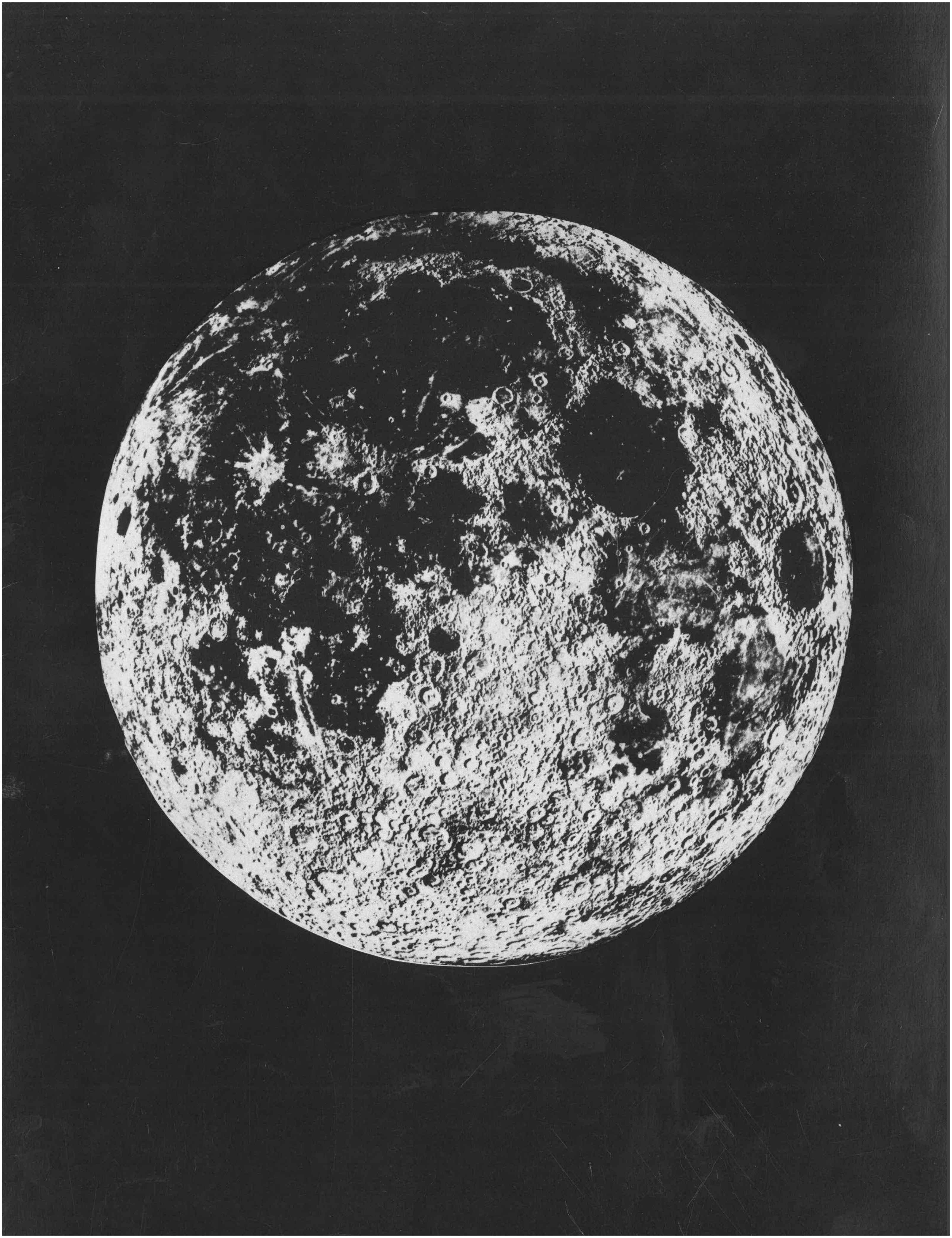

BACKGROUND
on the
GUIDANCE AND NAVIGATION SYSTEM
for the
PROJECT APOLLO SPACECRAFT

SYNOPSIS

For Project APOLLO, the U. S. effort to send men to the moon and back, the Instrumentation Laboratory, Massachusetts Institute of Technology, under contract to the Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas, has several roles. These include:

(1) Conception, design and development of the guidance, navigation and control systems used both in the APOLLO command modules and the APOLLO lunar modules.

(2) Support to NASA in monitoring systems from production through testing through spacecraft installation through launch from Cape Kennedy to ensure achievement of mission flight objectives.

(3) Development of the programs for the on-board guidance and navigation system computer for each APOLLO mission.

(4) Generation of test procedures for G&N at the Kennedy Space Center, Cape Kennedy, Fla., during checkout and prelaunch countdown including the generation of data for computer initialization prior to launch.

(5) Support for mission controllers at Cape Kennedy and at Houston, Texas, during missions to assist in solving problems if they arise. Support is provided by engineers at the two locations and by engineers at the Laboratory in contact with the control centers via restricted telephone lines.

(6) Analysis of post-flight data to determine system and spacecraft performance following a mission.

(7) Training of APOLLO crews in the general principles of space guidance and navigation, in the use of the APOLLO G&N systems in general, and, by using simulation devices, in carrying out specific mission segments as programed in the flight computers.

The Laboratory's contributions to APOLLO are primarily conceptual, intellectual, educational. All production is carried out by private industry working under direct contracts from the National Aeronautics and Space Administration. MIT receives no fee for the APOLLO work or for any of the numerous other programs carried out by Instrumentation Laboratory on behalf of the federal government.

THE SYSTEM CONCEPT

The guidance and navigation system that three APOLLO astronauts use to steer their way to the moon and back is self-sufficient, flexible and makes maximum use of the capabilities of both man and machine.

The system is self-sufficient in that it can be programed to perform, on board and in flight, all guidance and navigation functions for an entire mission, including aborts, with no aid from the ground. There is present, however, a redundant operational capability from the ground via tracking networks and radio links.

The system is flexible in that it can be used in alternative ways and modes to accomplish the complex task of guiding and navigating men to the moon and back. For example, in-flight modifications to flight plans and trajectories are easily accommodated if necessary.

By coupling what men do best (pattern recognition in sighting stars and landmarks, decision making, etc.) with what machines do best (tedious and repetitive computation, high-speed switching, etc.) the engineers and scientists responsible for design were able to evolve a system that offers the crew many operational options and aids in carrying out their mission efficiently.

System theory, mechanization, mission programing and the ability of men to use the system effectively are all continually tested and proved out on analog and digital simulation devices which include APOLLO command module and lunar module mock-ups. The devices also are used by APOLLO crews from time to time to familiarize themselves with the G&N system as part of their training activities.

THE SYSTEM HARDWARE

The system consists of three major sub-units -- inertial measurement unit (IMU), computer unit and optical unit.

Inside the spacecraft, the guidance and navigation system is mounted on the wall of the lower equipment bay at the feet of the astronaut occupying the middle couch. Wall area occupied is about four feet high and three feet wide.

All known methods of obtaining data for guidance and navigation are used -- inertial, celestial, on-board radar, and ground tracking.

The inertial measurement unit is a sphere 12 inches in diameter. The IMU holds a stable on-board frame of reference and measures spacecraft accelerations within this frame of reference. It has been called "astronomy in a closet". This frame of reference remains as fixed as the inertial space of the stars and it is from this that the term "inertial guidance" was coined.

At the heart of the IMU sphere are three gyroscopes and three accelerometers recessed into a metal fixture. The instruments and the fixture make up the stabilized inner member. This is suspended inside three concentric spherical gimbals connected to each other by drive motors and angle (readout) resolvers. The gimbals give the IMU its spherical appearance.

The gyros and accelerometers are single-degree-of-freedom. They sense motions acting only along and rotation about their input axes. These axes are aligned orthogonally, one for each of the three principal directions of movement (up-and-down, side-to-side, back-and-forth -- or pitch, roll and yaw). By summing what each instrument senses, the G&N system determines the resulting actual movement and takes appropriate action.

The job of the gyros is to sense instantaneously movements that would disturb the stable orientation of the inner member and counter this with compensating drive signals to rotate the gimbals appropriately. The job of the accelerometers is to measure acceleration forces acting on the spacecraft -- and, hence, changes in spacecraft direction and position -- within the gyro-stabilized frame of reference.

IMU information about spacecraft position, direction, velocity and acceleration -- in other words, the navigational and guidance data obtained by this inertial technique of astronomy from inside a closet -- flows to the guidance computer and is used, among other data (i.e., that from optics and that from ground tracking), in generating appropriate control signals for the spacecraft rocket system.

Since the IMU is often turned off during long periods of free coasting trajectory in order to save electrical power, it requires initial realignment to the stars before each use. One of the jobs the astronaut-operator has is IMU alignment using the G&N optical unit.

The optical unit consists primarily of a wide-angle-of-view scanning telescope of unity power and a 28-power magnification narrow-field-of-view space sextant. The astronaut uses the scanning telescope to locate desired star fields and landmarks. He uses the sextant to indicate directions to the stars and angles between stars and features on the near planets for navigation data.

The optical unit and the IMU are mounted on a common navigational base of maximum structural integrity. The point here is that, for IMU alignment, the frame of reference inside the IMU must be brought into precise alignment with the celestial frame of reference measured by the optics from time to time. If the sub-units were out of line with respect to each other, this would be impossible.

The guidance computer is a general-purpose digital machine of versatile design configured for deep space flight use. Basic word length in parallel operations is 15 bits with an added bit for parity check. The instruction code includes sub-routines for double and triple precision operations. Memory cycle time is 11.7 microseconds; single addition time is 23.4 microseconds. Core rope, used for fixed memory, has a capacity of approximately 36,000 words. Erasable memory, with a capacity of 2,048 words, consists of ferrite core planes. The processor portion is formed from integrated circuits. Total computer weight is 65 pounds.

Astronaut and computer communicate in a number language via the DSKY (pronounced disky and standing for "display and keyboard"), -- a 21-digit character display and 19-button keyboard. Two-digit numbers represent programs, verbs and nouns. Five-digit numbers stand for data such as position, velocity, etc. The astronaut punches data and commands into the system. These are displayed to him for verification in counter-type readout windows. The computer communicates with the astronaut by displaying readout numbers in the same windows. (When the computer requests the astronaut to take some action, the numbers flash in a periodic way to attract attention.)

Two other sub-units complete the system. The Power Servo Assembly (PSA) converts power from the spacecraft main power supply into various required currents and frequencies and amplifies servo-mechanism signals. The coupling and display unit (CDU) provides the signal interface between the computer and the angles associated with the IMU and optics. The CDU is electronic; the astronaut commands the IMU and optics through the computer.

The command module G&N system and the lunar module G&N system are almost identical, except that in the lunar module system the telescope is somewhat different than the one in the command module and there is no sextant.

The industrial team which produces the systems is headed by AC Electronics Division of General Motors Corporation, Milwaukee, Wis. As prime contractor to NASA, AC Electronics is responsible for manufacturing, assembly, testing, and subsystem integration.

Subcontractors to AC Electronics for major subsystems are Space and Information Systems Division, Raytheon Co., Sudbury, Mass., for the digital computer, and associated display and keyboards;and Kollsman Instrument Corporation, Syosset, N.Y., a subsidiary of Standard Kollsman Industries, Inc. for the optical subsystem. Sperry Gyroscope Co., Great Neck, N.Y., supplies the accelerometers under a direct contract from NASA. This same industrial team provided industrial support for the MIT design and development effort.

THE SYSTEM SOFTWARE

A major part of the APOLLO effort at Instrumentation Laboratory is the development of the flight guidance computer programs for each APOLLO mission. The fixed core rope memory units in the computers consist of tiny nickel-iron cores woven together by copper wires rope-fashion and encapsulated in plastic by the computer manufacturer, the Raytheon Co. The programs for each mission determine the core rope wiring sequence and, hence, programs for individual missions must be written and verified error-free before the memory units for the missions can be fabricated.

Developing and verifying the program for a particular mission requires, typically, about a year. NASA's Manned Spacecraft Center at Houston transmits to Instrumentation Laboratory a description of the functions that will be required of the G&N system. Working with MSC engineers, the Laboratory first develops a Guidance System Operations Plan (GSOP), a specification document sometimes three or four inches thick, which sets forth how the G&N system will perform its functions in careful detail and under all possible conditions.

The GSOP then is used to develop the mission program -- the sequence of coded instruction plus the library of needed basic information such as star charts and mathematical constants. Primary tools used in generating the program are powerful, scientific, general-purpose computers. Updates and revisions in the program are made continuously to reflect alterations in the mission profile.

Verification of the programs to ensure that they will perform the missions as prescribed is an equally important task. This verification is carried out using general-purpose computers. These include two Honeywell 1800s, two IBM 360/75s, and two SDS 9300s.

More recent programs, particularly those that are used in manned flight, are further verified using analog-digital hybrid computer techniques, command module and lunar module simulators, and actual flight computers. The Laboratory operates two analog-digital hybrids supplied by Beckman Instruments, Inc., Richmond, Calif.; one linked to a lunar module simulator, the other to a command module simulator. The hybrids simulate all APOLLO systems and all the dynamics of a particular mission. The mission program itself is operated on a "core rope simulator" developed at Instrumentation Laboratory. An actual flight computer is used for all other computer functions.

The same system of verifying the mission flight programs also is used to train the APOLLO crews in operating the G&N system during the missions to which they are assigned.

When a flight program is completed and verified, the general-purpose computers are used to produce magnetic tapes which are forwarded to Raytheon for use in operating the machines that weave the core rope memories. A typical mission requires weaving tape and checker tape, the latter to ensure that the weaving corresponds precisely to the programed instructions.

MIT engineers responsible for the programing effort began the practice of giving each mission flight program an identifying name. The practice was informal to begin with, but has since been adopted as official nomenclature associated with Project APOLLO.

The program that controlled an unmanned command module in the suborbital APOLLO flight test was called CORONA. Other programs are:

SOLARIUM	unmanned earth orbital command module flight program.
SUNBURST	unmanned earth orbital lunar module flight program.
SUNDISK	manned earth orbital command module flight program.
SUNDANCE	manned earth orbital lunar module flight program.
COLOSSUS	the flight program for the command module for manned flight to the moon.
LUMINARY	the flight program for the lunar module for manned flight to the moon.

LABORATORY APOLLO GROUP

The director and founder of the Instrumentation Laboratory is Dr. Charles Stark Draper, Institute Professor Emeritus and Professor Emeritus of Aeronautics and Astronautics. Dr. Draper is a former Head of the Department of Aeronautics and Astronautics and has been associated with MIT since he entered the Institute as a student in the early 1920s. He holds three MIT degrees -- S.B. 1926, S.M. 1928 and Sc.D. 1938.

Principal engineers in the Laboratory APOLLO group -- many of whom also hold degrees from MIT -- include Ralph R. Ragan (S.M. '52), Deputy Director for all NASA programs, and David G. Hoag (S.B. '46, S.M. '50) a Laboratory Associate Director who heads the APOLLO program specifically. Mr. Ragan earlier directed the Laboratory's design and development of the POLARIS missile guidance system for the U.S. Navy. Mr. Hoag was Technical Director of the POLARIS program.

Dr. Richard H. Battin (S.B. '45, Ph.D. '51), an Associate Director of the Laboratory, is APOLLO Technical Director for Mission Development and is an authority on astronautical guidance theory. Norman E. Sears (S.M. '52), another Associate Director, is the APOLLO Technical Director for mechanization of the G&N system. Eldon C. Hall (S.B. '53) leads the team which designed the flight computer and Lewis E. Larson, Jr. (S.M. '47), is Management Director in charge of the scheduling and financial aspects of the APOLLO program.

Working with Mr. Sears in mechanization design are: Ain Laats, in overall charge of system development; Jerry Gilmore (S.M. '67), in charge of the inertial subsystem; Glen Ogletree (S.M. '61), in charge of navigation sensors; and John Barker, in charge of electronics.

Working with Dr. Battin in Mission Development is Dr. F.H. Martin (S.M. '59, Sc.D. '65). Flight computer programing is performed in Mission Development with: Dr. Donald C. Fraser (S.B. & S.M. '63, Sc.D. '67), in charge of Control and Flight Dynamics; G. Levine (S.B. '57), in charge of space guidance analysis; M.H. Hamilton, in charge of Guidance Programs; and J.L. Nevins, Jr. (S.M. '56), in charge of display and human factors. S.L. Copps, is project manager for the COLOSSUS program; G.W. Cherry is project manager for the LUMINARY program.

THE MIT INSTRUMENTATION LABORATORY

The MIT Instrumentation Laboratory is no stranger to automatic guidance, navigation and control systems. In fact, work on manned spacecraft guidance and navigation was initiated at the Laboratory in early 1961 even before the Project APOLLO lunar effort was adopted as a major national goal. When President Kennedy announced this goal May 25, 1961, the Laboratory already had established the basic guidance and navigation concepts required and -- in response to federal request -- initiated a design and development program quickly.

Professor Draper pioneered the development of -- and, indeed, coined the name for -- inertial guidance and navigation systems for airplanes, ships, submarines, missiles, satellites and spacecraft in this country. Because of his work, Dr. Draper is internationally known as the father of inertial guidance.

MIT receives no fees or profits for the work the Laboratory does. Sponsoring agencies simply reimburse the Institute for the costs incurred in operating the Laboratory. As a national resource of talent and skill built up over the years at the request of sponsoring federal agencies, MIT makes the Laboratory available to help to the extent that it can in the achievement of national goals. The benefits that accrue to MIT are the educational contributions the Laboratory makes to the undergraduate and graduate educational programs offered by the Institute.

The Laboratory is an environment where graduate students, working under supervision of skilled faculty, engineers and scientists, may carry out thesis research leading to advanced degrees. In addition, Laboratory research generates new technology and knowledge for courses that are quickly incorporated into the regular Institute curriculum.

An illustration of the Laboratory's link to education is Dr. Draper himself. He was for many years both Head of the Department of Aeronautics and Astronautics as well as Director of the Laboratory. Scores of his students from the Department have performed their thesis research under his supervision at the Laboratory and have gone on to occupy positions of major responsibility in national defense and space programs.

Eight NASA astronauts hold MIT degrees. Of these, six earned degrees in Aeronautics and Astronautics through thesis research conducted at, or in connection with, the Laboratory. The six include: Lt. Col. David R. Scott (S.M. '62, Eng. '62), Lt. Col. Edwin E. Aldrin (Sc.D. '63), Russell L. Schweickart (S.B. '56, S.M. '63), Lt. Cmdr. Edgar D. Mitchell (Sc.D. '64), Capt. Charles M. Duke (S.M. '64), and Dr. Phillip K. Chapman (S.M. '64, Sc.D. '67). Schweickart also was a member of the Measurement Systems Laboratory staff before becoming an astronaut. (Dr. Chapman was among 11 scientist-astronauts selected in 1967. Two other MIT men -- Dr. William B. Lenoir (S.B. '62, S.M. '62, Ph.D. '65) of the MIT Research Laboratory of Electronics, and Anthony W. England (S.B. '65, S.M. '65) of the Department of Geology and Geophysics -- also are among the scientist-astronauts.)

The number of advanced degrees based on student research performed under the Laboratory's full spectrum of projects averages about 60 a year. During the three-year period 1964-67, MIT awarded 175 degrees which were based on thesis research at the Laboratory. These include 22 doctoral degrees, four engineer degrees, 131 master of science degrees and 18 bachelor of science degrees. During the period the Laboratory has been designing the APOLLO G&N system, 60 students have completed theses based on APOLLO-related research and leading to doctor of science, engineer, master of science and bachelor of science degrees. Students come not only from the Department of Aeronautics and Astronautics, but also from such other departments as Electrical Engineering, Mechanical Engineering, Physics and Mathematics. All three military academies annually send outstanding graduates to MIT for graduate study at the Instrumentation Laboratory.

New courses constantly evolve out of Laboratory research. The Department of Aeronautics and Astronautics has been teaching classes in guidance and control developed out of Laboratory research for more than 25 years. One of the early faculty members who began teaching courses based on Laboratory research was Dr. Robert C. Seamans, Jr. (M.S. '42, Sc.D. '51), formerly Deputy Administrator of NASA and now Secretary of the Air Force, who earned his own doctoral degree via thesis work at the Laboratory.

Professor Walter Wrigley (S.B. '34, Sc.D. '41), Laboratory educational director, began offering the first regular course in inertial guidance in the mid-1950s. Dr. Richard Battin, who heads the Laboratory group working out computer programs for APOLLO missions, also teaches a course in astronautical guidance. In all, more than 20 different courses, now a regular part of the MIT curriculum, have grown out of the research projects carried out at the Laboratory.

Dr. Draper started the Laboratory just prior to World War II to develop lead-computing gyroscopic gunsights for Navy anti-aircraft guns. His Mark 14 gunsight was the first of its kind to reach the fleet and played an important role in naval engagements of World War II.

Toward the end of World War II, Dr. Draper and his associates developed gyro-stabilized gun-bomb-rocket sights for Air Force fighter planes and one of these saw extensive service in the Korean War aboard F-86 fighters.

Following World War II, Dr. Draper began applying knowledge of gyroscopic stabilization and feedback control to the original work done in this country on inertial navigation and guidance. Interest in this work actually originated with Dr. Wrigley's own doctoral thesis research supervised by Dr. Draper in the late 1930's.

Dr. Draper made his first inertial system transcontinental test in an airplane flight from Massachusetts to Los Angeles in 1953, demonstrating feasibility of such systems. Since then from the Laboratory have come designs and design concepts for many now-operational systems.

In APOLLO, as in all of its programs, the Laboratory works closely with government-selected participating contractors in developing system designs, fabricating prototypes, carrying out engineering design tests and supporting operational use. System production and manufacturing, of course, is performed by industry. Of federal funds expended for design, development, test and procurement of these systems, the bulk goes to the participating industrial contractors for manufacture and fabrication, and only a small portion to support MIT's design, test and operational support efforts.

The Moon Show
Hayden Gallery
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