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HOW DOC DRAPER BECAME THE FATHER OF INERTIAL GUIDANCE

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With Missouri roots, a Stanford Psychology degree, and a variety of MIT degrees, Charles Stark "Doc" Draper formulated the basis for reliable and accurate gyro-based sensing technology that enabled the first and many subsequent inertial navigation systems. Working with colleagues and students, he created an Instrumentation Laboratory that developed bombsights that changed the balance of World War II in the Pacific. His engineering teams then went on to develop ever smaller and more accurate inertial navigation for aircraft, submarines, strategic missiles, and spaceflight. The resulting inertial navigation systems enable national security, took humans to the Moon, and continue to find new applications. This paper discusses the history of Draper's path to becoming known as the "Father of Inertial Guidance."

FROM DRAPER'S MISSOURI ROOTS TO MIT ENGINEERING

Charles Stark Draper was born in 1901 in Windsor Missouri. His father was a dentist and his mother (nee Stark) was a school teacher. The Stark family developed the Stark apple that was popular in the Midwest and raised the family to prominence[1] including a cousin, Lloyd Stark, who became governor of Missouri in 1937. Draper was known to his family and friends as Stark (Figure 1), and later in life was known by colleagues as Doc.

During his teenage years, Draper enjoyed tinkering with automobiles. He also worked as an electric linesman (Figure 2), and at age 15 began a liberal arts education at the University of Missouri in Rolla. After 2 years he transferred to Stanford University where he got a Psychology degree om 1922.[1,2] While at Stanford he developed an interest in chemical and electrical instruments upon observing their inaccuracies as used in the psychology lab.[3]

After his graduation from Stanford, Draper drove with friends across the continent (through Canada) to Boston (Figure 3). Upon their crossing the Charles River from Boston to Cambridge, the new MIT campus attracted his attention. As his friends went on to see Harvard, Draper wandered about MIT.[2] Upon seeing an electrochemical engineering course in a catalog in the MIT admissions office, he asked if he could enter MIT. He was told there was a vacancy and given his degree from Stanford, he could enter by paying a year's tuition ($250) and a promise to spend the next two summers working on mathematics courses he should have taken before applying. Shortly after he also registered as a student in the Army Air Corps Reserve Officers Training Corps.[4]

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Figure 1. Draper as a Child.

Figure 2. Draper as a Teenage Electrical Wireman.

Figure 3. Draper During a Transcontinental Excursion by Car.

Draper spent the next four years earning a bachelor’s degree in electrochemical engineering, receiving the degree in 1926. In parallel, he received a commission in the Army Air Corp as a Second Lt., going to Brooks Field (San Antonio, TX) upon MIT graduation (Figure 4). Draper washed out of the flight school four months into the six-month program. Overcoming his disappointment, he took a job in New York working on an infrared signaling project for R.E. Gilmore who had just resigned as President of Sperry Gyroscope to start a research and development lab that included the Draper’s work. There Draper studied the use of infrared radiation for communications and locating targets. Though resources were very limited, Draper was able to construct a primitive proof-of-concept demonstration device that suggested that infrared-sensitive receivers could be developed into practical instruments. However, Navy funding for the project ended, and Draper looked for a new job.[4]

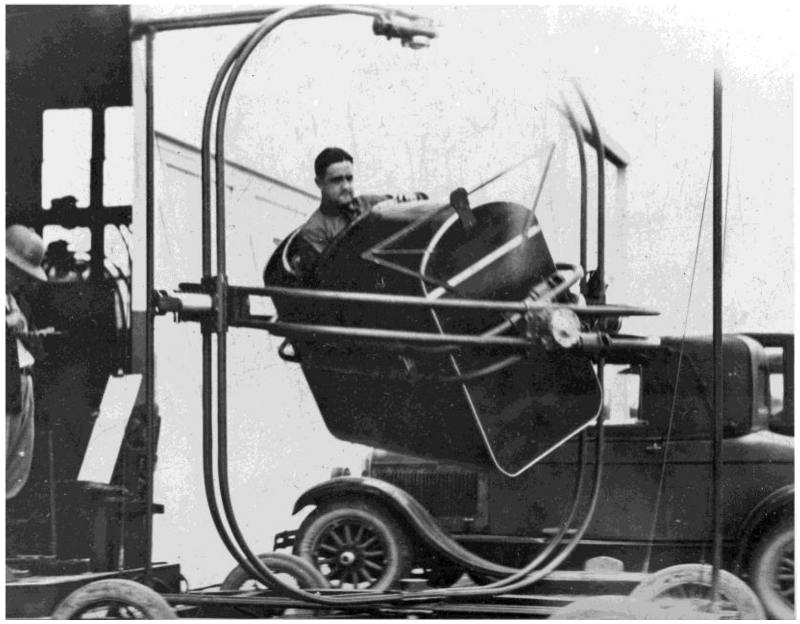


Figure 4. Draper in an Early Flight Simulator.

ORIGIN OF MIT'S INSTRUMENTATION LABORATORY

After his New York work ended, Draper returned to MIT (in 1928) as a Research Associate on a fellowship sponsored by a General Motors grant to work on the spectroscopy of fuel flames in the cylinders of internal combustion engines. That work was done in the Aeronautical Power Plant Lab of the Aeronautical Engineering Department. While doing that work, Draper registered for a Master's Degree program that combined aeronautics, physics, and chemical engineering. In 1929 he also earned a civilian pilot's license.[4]

Draper's combustion research morphed into a study of high frequency pressure variations during combustion associated with "knocking." This led the development of knock-indicator instruments under the sponsorship of Sperry Gyroscope, including a cylinder head-mounted accelerometer. In the same time frame, Prof. William Brown left MIT to work on blind instrument flying experiments under the leadership of Jimmy Doolittle and the sponsorship of Harry Guggenheim. Brown had been teaching an Aircraft Instruments course at MIT, and it was left to Draper (still then a Research Assistant) to take responsibility for teaching the course. Draper enthusiastically took on what he then called Informetics that he expanded from just sensing, processing, and comparing information to newly include practical applications of control, navigation, and guidance.[4] Julius Stratton, then a Professor at MIT and subsequently its President, observed that he was never knew who was the instructor and who was the student in Draper's class. [2]

During the 1930s, Dr. Jerome Hunsaker and Professor Fay Taylor, convinced the Navy to provide a contract to measure the vibration in aeronautical engine crankshafts. Professor Taylor conceived an undamped vibration absorber that could eliminate the crankshaft vibration problem, and left Draper in charge of the associated instrument design problem. Draper worked with students, to design, build, and flight test the resulting systems until the results were satisfactory to the Navy (those systems became the MIT Sperry Vibration Measuring Equipment). Leveraging off Draper's knock-detection research, Taylor, Draper, and their laboratory team also developed an engine analyzer that Sperry manufactured in large numbers for use on multi-engine, longrange aircraft. These devices enabled aircrews to run aircraft engines as lean as possible, short of knocking, maximizing aircraft range for any given takeoff fuel load.[2, 3,4]

Many factors influenced the direction of Draper's career in the 1930s. His aeronautical power plant work led to much in-flight testing work, which facilitated and sustained his involvement in development of theory for aircraft instruments and control. He spent time at the Boeing School of Aeronautics in Oakland where he tried out the "Link Trainor" (Figure 5) that was a ground simulator being used to train pilots for instrument flying. This spawned Draper's interest in needed improvements to aircraft bank and turn indicators that led to his work on gyro-based inertial navigation technology.[3]

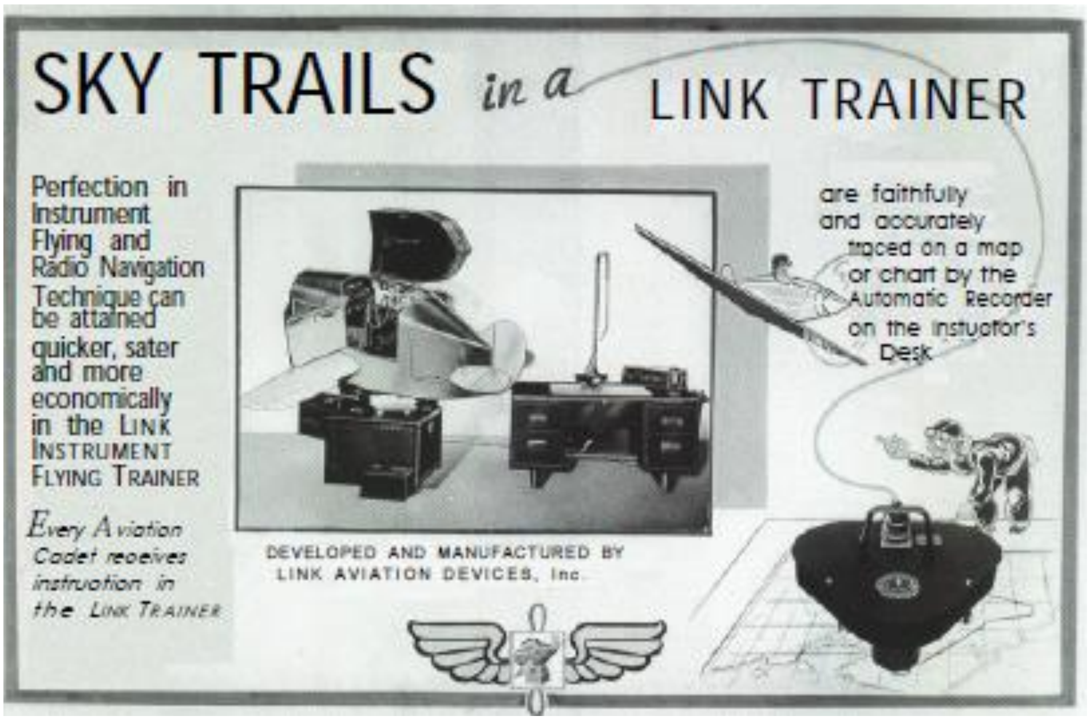


Figure 5. Promotional Literature from the 1940s for the Link Trainer.[5]

By the mid 1930's Draper became an Associate Professor at MIT. In 1938 he got his PhD from MIT in Physics, and by 1939 he was a Full Professor. Meanwhile, he, his faculty colleagues, and his students had built up what would become known as the MIT Instrumentation Laboratory.[1, 2]

APPLYING GYROSCOPES AS MOTION INSTRUMENTS

Draper's early flying experiences had convinced him that better aircraft turn indication was needed. In the early 1930s the state of the art was air-jet-driven, spring-restrained, single-degree-of-freedom gyros carried by ball bearings. Draper realized that aircraft operational vibration caused dents in the bearing races that could lead to erratic sensor readings. He believed that replacement of the ball bearing with spring suspensions and introduction of viscous damping could mitigate those sensor problems. During summer employment by Sperry Gyroscope, he worked with an aircraft instrument, mechanic, Harry Ashworth to develop and demonstrate spring-gimbal suspended, and damped gyroscopic sensors (Figure 6). Flight testing of prototypes were successful, stimulating pilot interest, but the on-going success of current Sperry instrument products diminished the company's interest in marketing of an alternate instrument. However, the parallel outbreak of World War II (WWII) indicated that targeting of guns against moving threats was deficient. It was immediately apparent to Draper that gyroscopic instruments mounted to guns mechanized to offset the gun aim point as a function of vehicle motion rates could greatly improve the gun targeting accuracy. Discussions of this idea with Sperry representatives resulted in some support as Draper returned to MIT to investigate use of his aircraft instrument design for gun targeting improvement. Harry Ashworth went with Draper to MIT to build a gunsight for engineering-level testing.

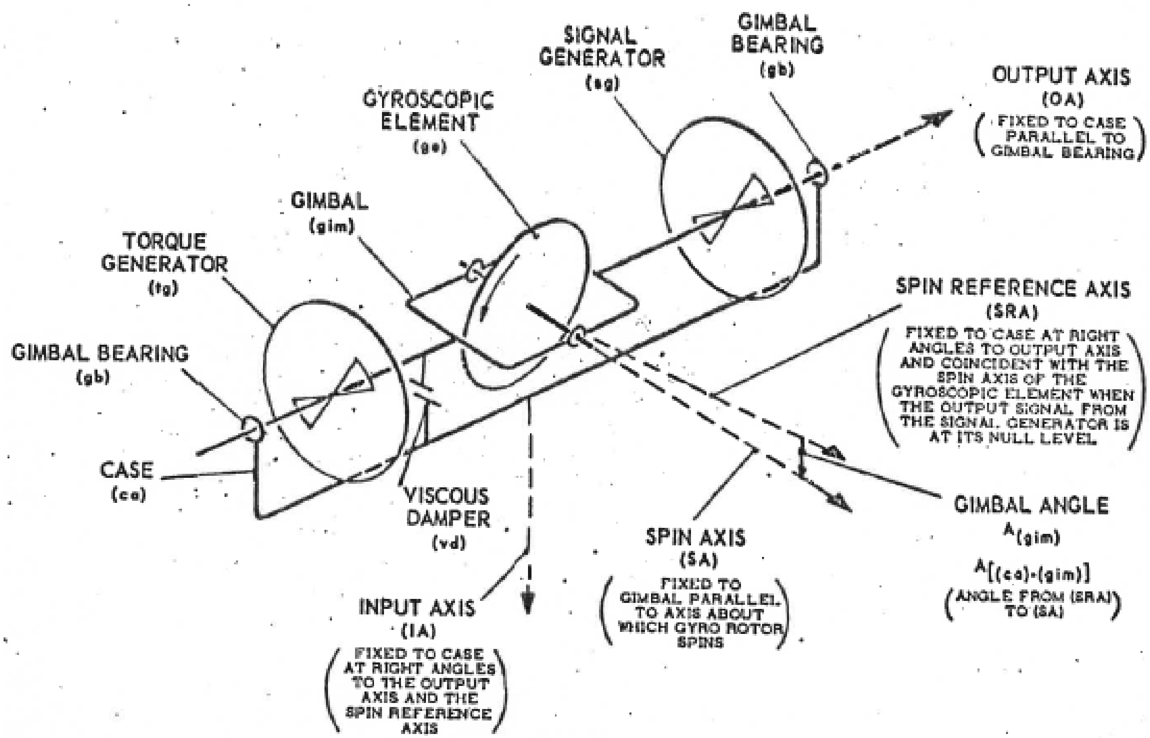


Figure 6. Draper' Gimbal-Mounted, Viscous-Damped Single-Axis Gyro Sensor.[3]

MAKING A BIG DIFFERENCE IN WORLD WAR II

Back at MIT in the fall of 1940, Draper leveraged his students (that included military officers) to help with theory, design, and testing of gyroscopic gunsights.[3] In the design they needed to compensate for the effects of sea state and the mechanical disturbances of rapid gun fire. Draper chose to utilize elastically suspended gyro gimbals with adjustable spring restraints and viscous damping that provided mechanical protection and output smoothing. Within one academic year, the team had a prototype ready for testing that was about the size and shape of a shoebox. A rudimentary test configuration was utilized that involved a towel with airplanes printed on it that was attached to a movable clothesline set about 75 feet away from a .22 caliber rifle with the gunsight attached gun (Figure 7). The tests were performed at in a concrete-walled range at the Army's Watertown Arsenal a few miles from MIT.[3] Because of its configuration, the gunsight took on the nickname of Doc's Shoebox" (Figure 8).

Initially there was no government or corporate interest in the new gunsight as in-production systems were deemed sufficiently good. However, the British were already immersed in WWII and British ships were not then being well protected by existing gun defenses. Sir Ralph Howard Fowler, a British physicist and ballistics expert, visited MIT and was impressed upon trying out the gunsight. He followed up by establishing contacts between the British Admiralty and Sperry that resulted in the company designing and manufacturing several gunsights for the British.[4] In parallel, the US Navy, on the advice of Naval officer students of Draper, took the gunsight to Dahlgren Proving Ground and tested in on a 20mm machine gun against airplane-towed sleeve targets. The excellent results of that test resulted in the government directing Sperry to produce the gunsights under Draper supervision.[3] World events also accelerated the gunsight development and deployment. On December 10, 1941, both the British Battleship Prince of Wales and its Battlecruiser Repulse were lost due to Japanese air attack off the Malay peninsula, proving the inefficacy of the then fielded ship defense gunsights against advancing aerial warfare capabilities.[6]

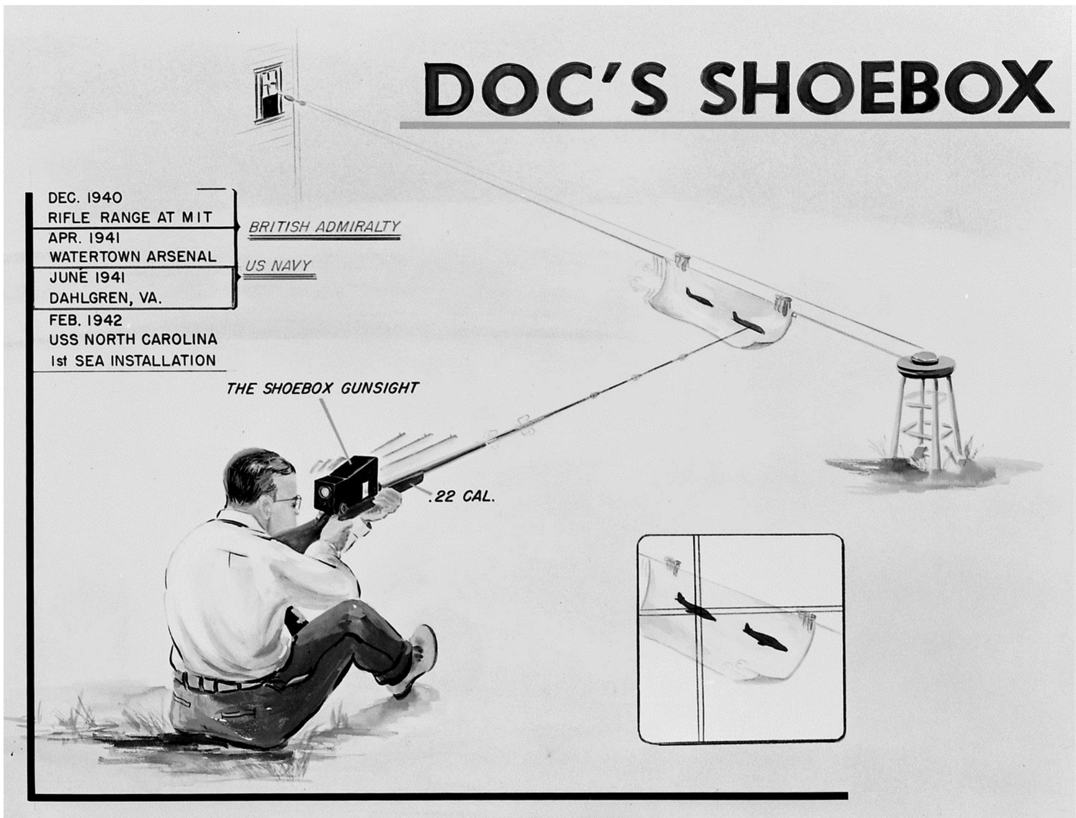


Figure 7. The Initial Test Arrangement for Draper's Gimbaled, Target-Lead-Enabled Gunsight.

To expedite the gunsight readiness for field use, four rooms in the Aeronautics Department building at MIT were utilized to further the preliminary design, and built a dozen field-able prototypes that were successfully applied.[3] The resulting gunsight became known as the Mark 14. The true efficacy of the Mark 14 gunsight was demonstrated on October 26, 1942. It "Made the fleet relatively invulnerable to attack from aircraft…. In one engagement (it) enabled the battleship South Dakota to shoot down 32 … planes."[7] The Mark 14 "succeeded not because of the quality or precision of its computation, but rather because of its compromises. Estimating range provided the most significant shortcut. Rather than using a bulky and slow rangefinder, the operator merely estimated range by eye and then dialed it in by hand" (quote from Prof. David Mindell at MIT).[8] About 100,000 Mark 14s were produced for use on a variety of platforms, including for many Naval ship defense guns (Figure 9).[3]

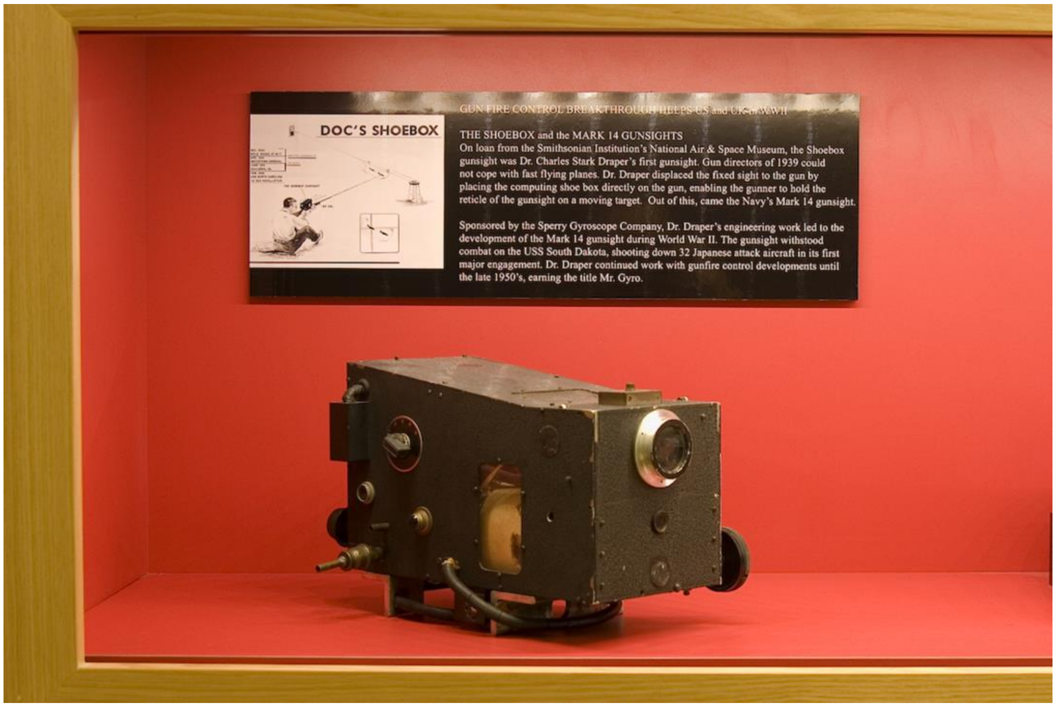


Figure 8. A Prototype Mark 14 (Doc's Shoebox) Gunsight.

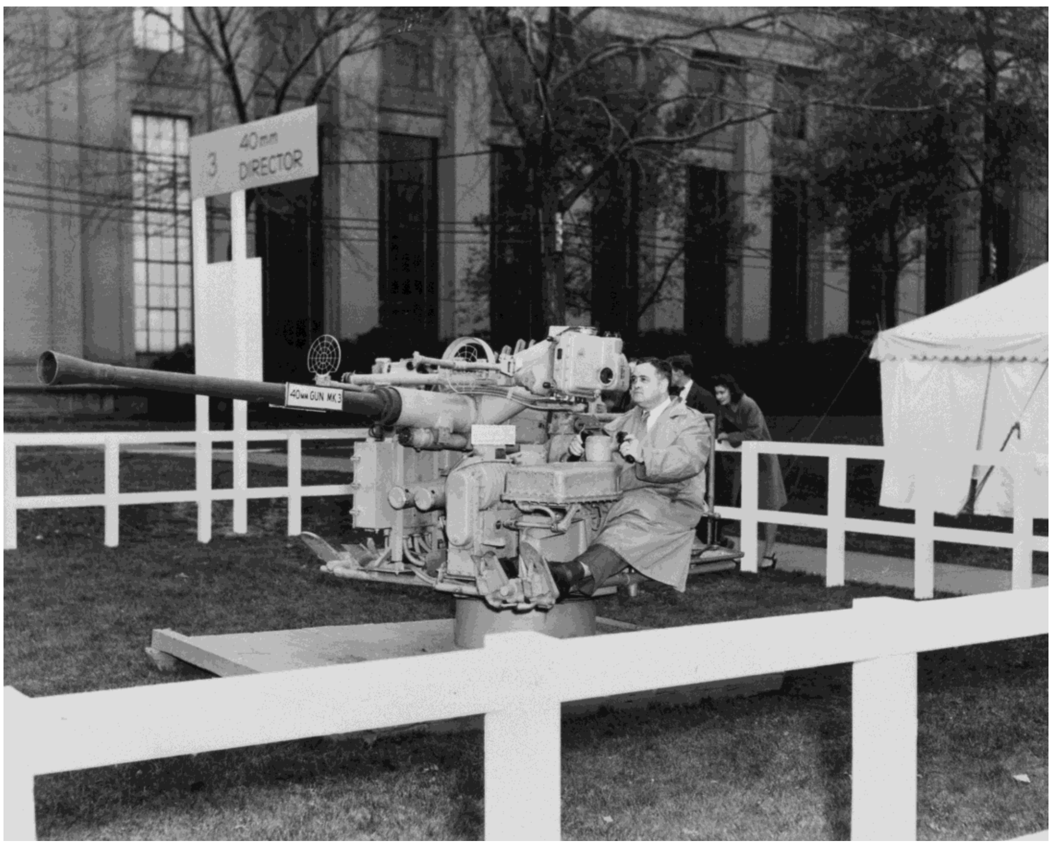


Figure 9. Draper Displaying a Naval Ship Defense Gun with an Integrated the Mark 14 Gunsight.

INERTIAL NAVIGATION FOR FLIGHT

By the late 1930s, Draper had graduate students pursuing "closed-box navigation solutions." Walter Wrigley's 1941 doctoral dissertation done under Draper established the theoretical basis for inertial navigation. This dissertation proposed using damped pendulous gyros as instruments on a vehicle to determine the changes in inertial state of the vehicle (Figure 10).[9] By the end of WWII, Draper and his team realized that improved gyroscopic instruments could provide "jam-proof" systems that could automatically navigate both manned and unmanned vehicles, regardless of weather, and without reliance on information from external sources.[10] In 1944, Draper and his former graduate student Leighton Davis (who was then at the Wright Field Armament Laboratory) began discussion of a self-contained inertial navigation system. This initially led to a 1945 contract to develop a self-contained aircraft bombing system with a target error not to exceed two miles after ten hours of flight, but with an initial instantiation allowing solar and stellar observations to enable evaluation of the inertial system performance.[2,11] This led to development and 1949 B-29 test flights of the 4,000 lb navigation system FEBE (named for the Roman sun god Phoebus) that used a star and magnetic coordinates as references. The FEBE test flights proved that inertial navigation was then feasible over moderate distances without stellar tracking.[8]

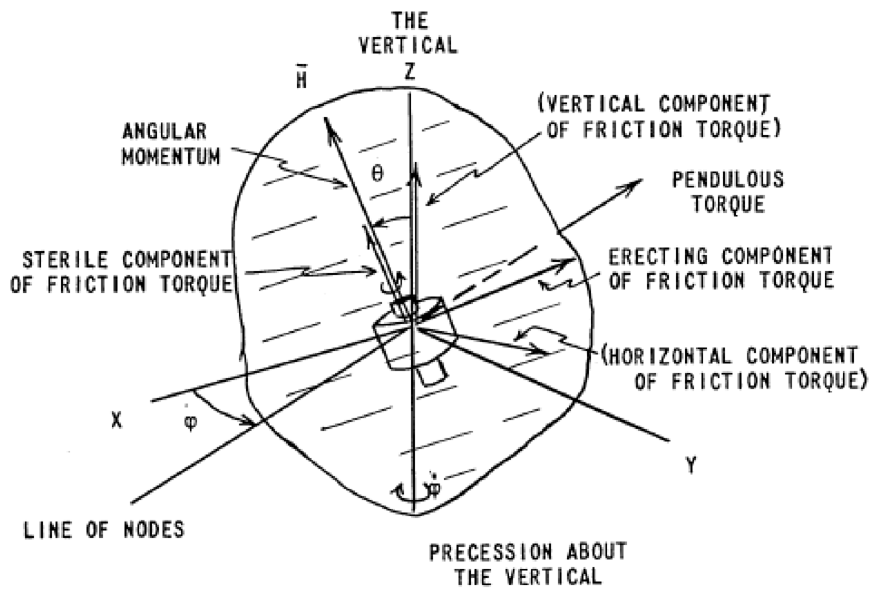
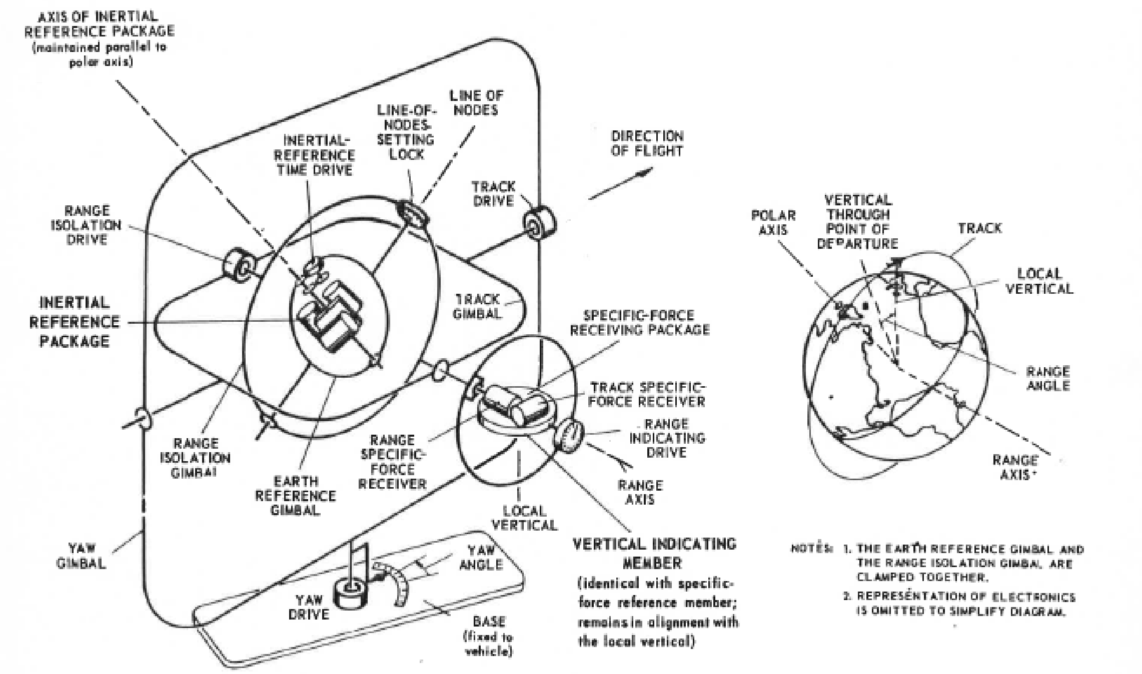


Figure 10. From the Doctoral Thesis of Walter Wrigley[9] – Illustration of How Torques Acting on a Damped Pendulous Gyro Mounted on Gimbals Could be Used for Inertial Navigation.

In parallel to FEBE testing, Draper's team began work on the Space Inertial Reference Equiment (SPIRE).[8] SPIRE was a purely inertial system. It had three orthogonally mounted single degree of freedom floated gyros for orientation data and three pendulous integrating gyro accelerometers, also orthogonally mounted on an inertial reference platform mounted within gimbals to isolate the platform from carrier vehicle motion (Figure 11).[3] The "floating" placed a dense Newtonian fluid (with viscosity independent of the shear rate) in a narrow gap between the gyros cylinders and their container. By having a Newtonian fluid, the effect of shear on the gyro readily factored into sensor signal interpretation. Temperature control was necessary to keep the fluid viscosity very close to the expected level.[2] An analog computer converted inertial coordinates to earth-relative data. The overall system was designed to keep navigation errors to less than one nmi after 10 hours of use in flight.[8]



Inertial guidance system that is based on an earth reference gimbal with a time drive from an inertial reference package and on a Schuler-tuned specific-force receiving package.

Figure 11. A Functional Diagram for the SPIRE Inertial Navigation System.[3]

A SPIRE system, was placed on a B-29 for flight evaluation (Figures 12-13). It weighed 3,000 lb – all the design work had focused on successful function, not minimizing its size. A one-hour shakedown flight was made on February 6, 1953. The next day it was used to navigate the airplane on autopilot for the entire flight from Bedford, MA to Los Angeles. It performed to specification, the results were documented that night, and they were presented the next day (February 8) at a Symposium scheduled to discuss the *possibility* (now proven) of totally inertial flight. With in-flight inertial navigation now proven realizable, all subsequent focus was to make much smaller navigation systems that would meet specific mission needs.[8]

Figure 12. Spire During B-29 Installation.

Figure 13. Draper, Eric Sevareid, and SPIRE on the B-29.

GUIDANCE FOR SUBMARINE-LAUNCHED MISSILES

Draper and his team began to apply inertial sensing technology to marine vessel navigation in 1948 with the Marine Stable Element (MAST) program.[10] The program sought to determine the vertical and azimuth with extreme precision using "specific force" sensors (Figure 14).[3] The first sea trials were in March 1954. In parallel work began on the Submarine Inertial Navigation System (SINS) that had its first sea trials in November 1954.[10] These ship navigation systems established a basis for providing a precision navigation initialization reference for missiles that could be launched from the ships.

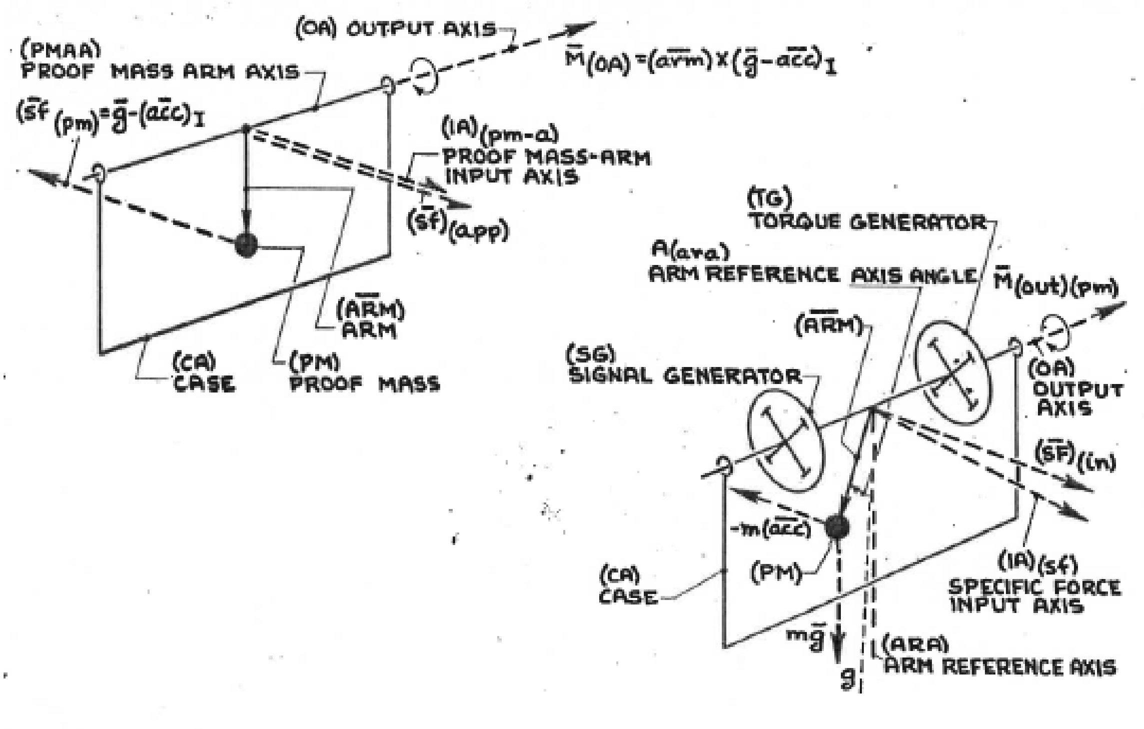


Figure 14. Draper's Basis for a Single-Degree-of-Freedom Proof-Mass-Arm Specific Force Sensors.[3]

In 1945 the Instrumentation Laboratory reported to the government that the possibility should not be neglected that a stellar-aided inertial bombing system could eventually be robotized for use with guided missiles. Draper and his team began work on the guided ballistic missile problem in 1953 in an arrangement with Consolidated Vultee Aircraft Corporation. Responsibility for that work was soon taken by the Air Force. The work had progressed enough by 1955 to apply it to the Thor Intermediate Range Ballistic Missile (IRBM). Resulting Instrumentation Laboratory technology and subsystem designs were turned over to the AC Spark Plug Division of General Motors to develop and manufacture the guidance system for Thor. The Thor successfully demonstrated closed-loop inertial guidance in December 1957.[10] This arrangement for between the Instrumentation Laboratory and AC Spark Plug for the Thor guidance system became a model for a guidance system government design agent role that the Instrumentation Laboratory would often subsequently follow.

While the Thor was nearing completion, Draper and his Instrumentation Laboratory Team were asked to design the guidance system for the submarine-launched Polaris IRBM.[10] The resulting inertial space-referenced MK1 guidance system (akin that that shown in Figure 15) came in at 225 pounds using printed circuit boards and a digital computer , with a Circular Error Probable (CEP) of about 2 nmi over the Polaris flight range.[8] The first fully inertial MK1 Polaris missile launch from a submerged submarine was on July 20, 1960 (Figure 16).[10]

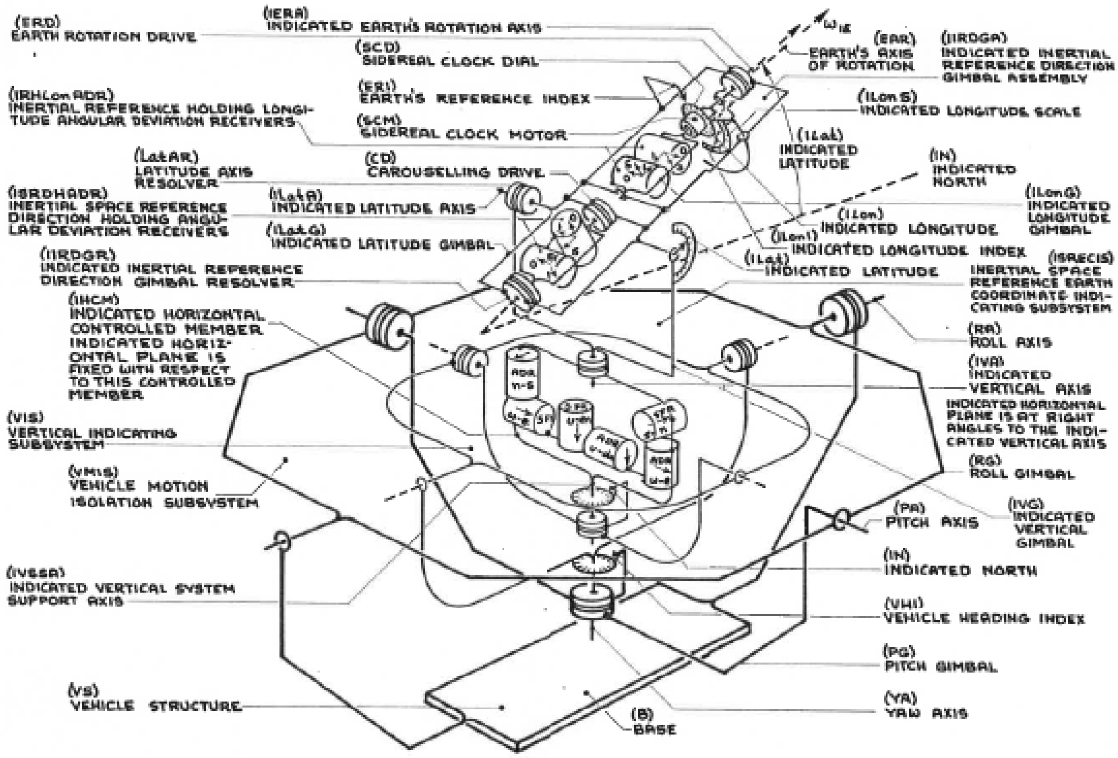


Figure 15. A Functional Representation of Draper's Inertial Navigation System with an Inertial Space Reference Earth Coordinate Indicating Subsystem[3].

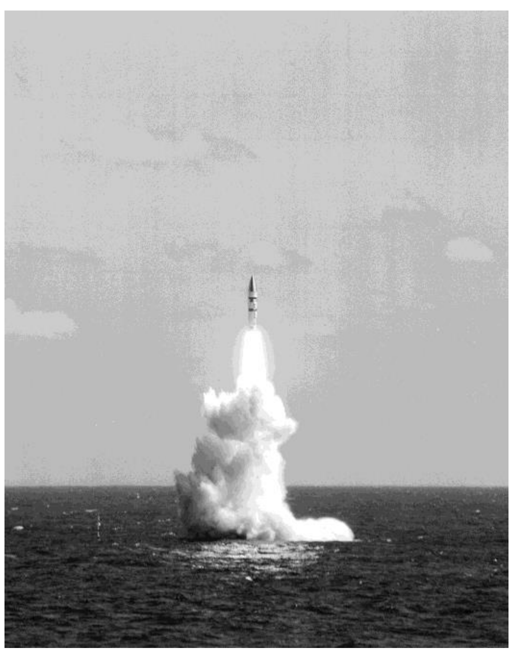


Figure 16. A Submarine-Launched Polaris with an Instrumentation Laboratory Inertial Guidance System.

The submarine ballistic missile guidance capabilities continued to advance. A MK2 version first launched on a longer-range Polaris in February 1962[10] weighing under 140 lb, and with a CEP of about 0.5 nmi.[8] After that, the Instrumentation Laboratory and its successor Charles Stark Draper Laboratory served as government design agents for the entire sequence of progressively more capable and precise Navy submarine-launched Intercontinental Ballistic Missile (ICBM) guidance systems (that included Poseidon, Trident I and Trident II). Applicable guidance system capabilities were also applied to a number of Air Force ICBM programs (e.g., Titan and Peacekeeper).

A KEY ROLE IN APOLLO

Soon after President Kennedy announced the goals for the Apollo program, Draper and Milt Tragesor, also from the Instrumentation Laboratory, had a meeting with NASA Administrator James Webb as well as Deputy Administrator Hugh Dryden and Associate Administrator Robert Seamans (another former Draper student). At that meeting Draper told the NASA leadership that the Instrumentation Laboratory had the means to conceive, work out theory for design, and oversee the construction of guidance and control systems for Apollo vehicles, as well as the ability to consult during use of those systems.[11] What Draper was proposing to the NASA Leadership would leverage work done in the late 1950s for the Air Force under the leadership of Milton Tragesor that addressed fully integrated, deep-space capable Guidance Navigation and Control (GN&C) technology, including required computing capabilities, to enable an unmanned Mars vehicle (Figure 17). That study for the Air Force was reported in five volumes in 1959 addressing a mission from Earth to Mars and back, with the vehicle imaging Mars at close range during a fly-by on film, with the vehicle and film then returning to Earth. Richard Battin and J. Halcombe Laning were also key contributors to the study (Figure 18), with Battin addressing interplanetary trajectories and guidance, while Laning, with Tragesor addressing use of a central computer that would enable execution of alternative courses of action as needed (in addition to its routine management of spacecraft functions).[12] Very soon thereafter, NASA issued the first Apollo contract to the Instrumentation Laboratory, with Sen. Leverett Saltonstall notifying the Laboratory of that selection by telegram on August 9, 1961.[8] Key leaders from the Polaris program work (e.g., David Hoag) would be utilized to apply their hard-learned system design and development expertise to Apollo. Draper's consultations with top NASA and US government leadership about Apollo and other program plans/status were on-going events (see Figures 19-20).

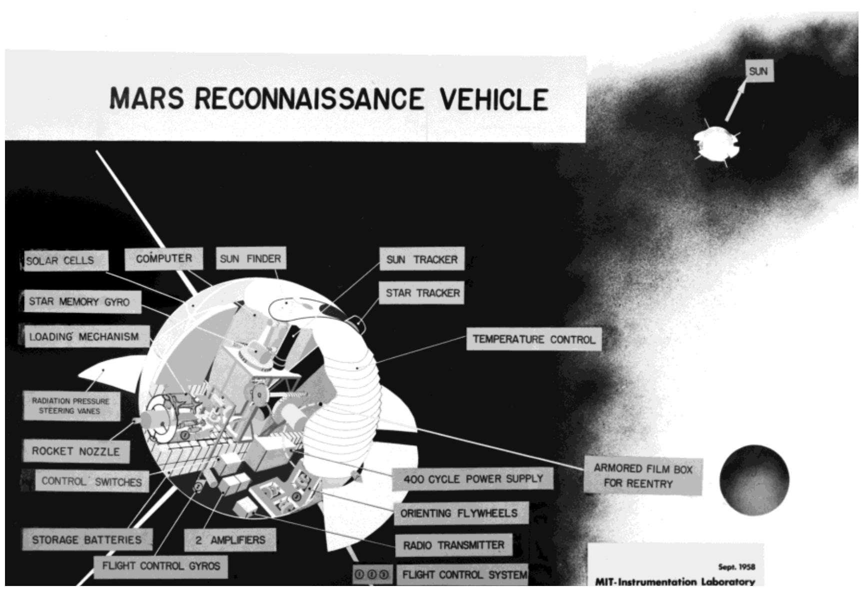


Figure 17. A Mars Mission Vehicle Concept Used as an Apollo Model.

Figure 18. (left to right) J. Halcombe Laning, Milton Trageser, and Richard Battin with a Model of the Proposed Mars Mission Spacecraft.

Figure 19. Draper with Wernher von Braun.

Figure 20. Apollo Discussion Aboard Air Force One with (left to right) Frederick Seitz, James Webb, Draper, and President Johnson. Seitz, a Solid State Physicist was then President of the National Academy of Sciences.

Development of a volume and power-limited computer and its software for management and control of all Apollo mission events was the most critical technology for achieving the goals of the program.[8] Getting the digital capacity into the allocated volume of 1 ft^3 necessitated clever memory design. The final computer design had 36,000 words of woven rope core memory that had its programing implementation frozen upon fabrication. It also had 2,000 words of Random Access Memory (RAM). If the RAM had relied on the transistors in prevalent use at the time, then the computer volume and power constraints could not have been met. Fortunately, at the time, Integrated Circuit (IC) technology was being developed. The state-of-the-art at that time would allow the equivalent of several transistors to be included on each IC chip. The Instrumentation Laboratory chose the IC technology, enabling a 12 microsecond clock speed. In 1963 the Instrumentation Laboratory consumed 60% of the US IC production for Apollo use, receiving more than 100,000 ICs by 1964[13] Also needed for the computer were processing-efficient GN&C algorithms, a compiler, and electronics design/integration expertise. Applicable design leadership in these disciplines was provided by Instrumentation Laboratory employees Richard Battin, J. Halcombe Laning, and Eldon Hall respectively. The Guidance system hardware was evolved from the Polaris system design, but with the addition of a stellar alignment capability that could compare crew optical sightings with computer gimbal angle readings from the inertial navigation system. That added optical update capability was a backup to ground-based ranging tracking updates in the event that the flight vehicle lost communi8caitons with the ground. A sextant was built into the installed Apollo vehicle guidance system for this purpose (Figure 21).

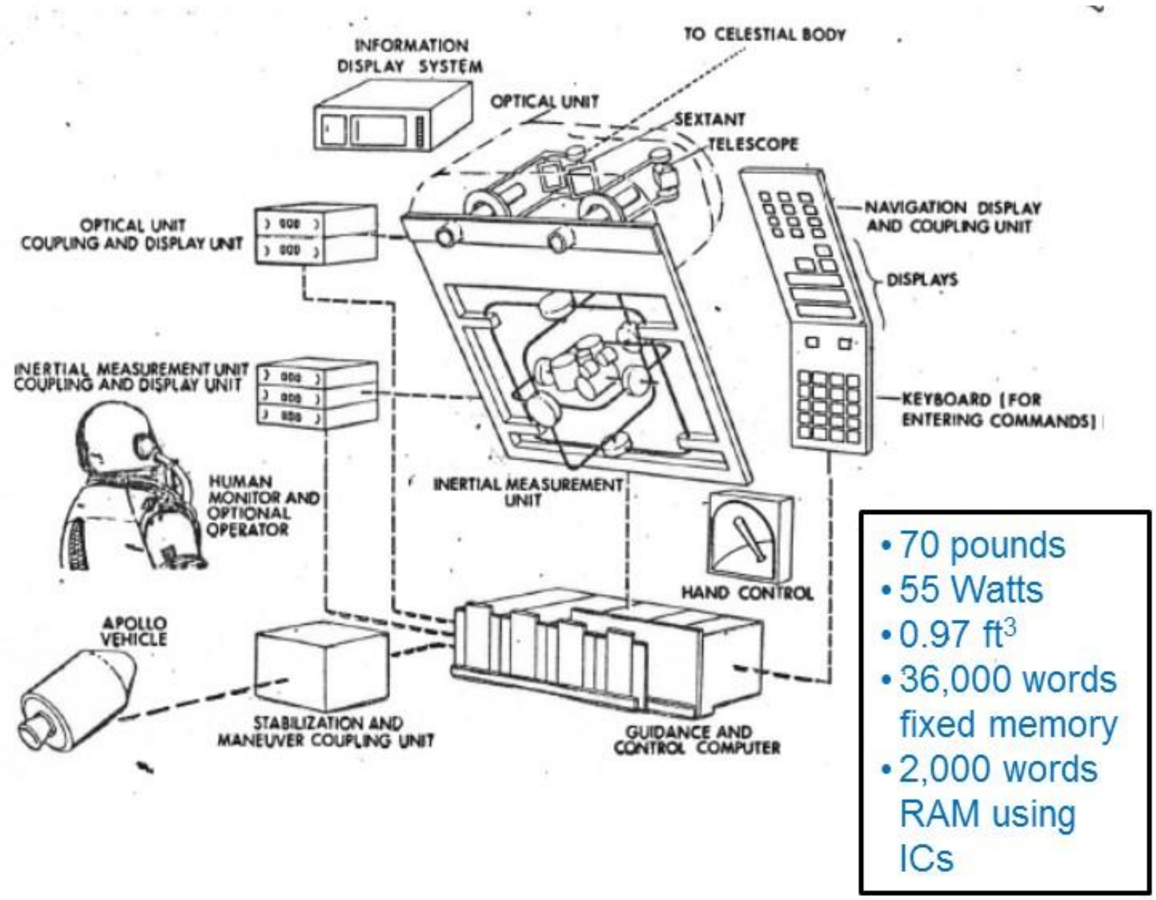


Figure 21. Schematic of the Apollo Guidance and Processing System.[3] (Computer Specifications are from Ref. 12.)

CHANGED DRAPER ROLE WITH THE BIRTH OF THE CHARLES STARK DRAPER LABORATORY

As the Instrumentation Laboratory grew, it occupied a variety of widely distributed buildings in Cambridge, MA. Much of its work related to strategic military systems. During the era of the Vietnam war, there was significant risk that, because of student pressure, the MIT leadership would restrict the scope of the Laboratory's work. That resulted in an amicable separation of the Laboratory from MIT in 1973, creating the Charles Stark Draper Laboratory, Inc. as a new, independent, not-for-profit institution with the objectives of developing technology in the national interest, and supporting advanced education of students in disciplines with ties to the corporation's research and development work. An important initial focus of the new organization was its financial survival as an independent institution. That resulted in a new management structure that placed Doc Draper in the position of Senior Scientist, and Robert Duffy as the President and Chief Executive Officer. Soon after its creation, the corporation began construction of a new home in Technology Square in Cambridge (very close to MIT) that consolidated its work force into one location. Doc Draper adapted to his new role by applying his accumulated expertise to addressing global policy issues (e.g., interacting with the White House regarding proposed Strategic Arms Limitation Treaties[14]), addressing student interests, and making presentations that addressed some of the history of the many amazing developments that his vision, invention, and design had enabled. Draper continued in these roles until he passed away in 1987. I was a Draper Fellow during that period, a graduate student at MIT doing my MIT Research Assistantship on projects at the Charles Stark Draper Laboratory. Draper was generous with his time with students, participating in many events with them, and providing career inspiration. I was privileged to have the opportunity during those years to interact with Doc Draper on a number of occasions.

HONORING DOC IN PERPETUITY: THE DRAPER PRIZE FOR ENGINEERING

The Nobel prizes provide a world stage for major scientific contributions, but there is no Nobel prize for engineering achievements. To mitigate that shortfall, the Charles Stark Draper Prize for Engineering was established, commemorating Draper's globally impactful engineering contributions by recognizing engineering achievements with major global impact by others of any nationality. The prize was established by the National Academy of Science at the request of the Charles Stark Draper, Laboratory, Inc.,[15] and is a preeminent global prize in that category. An aim of the prize is to improve public understanding of the importance of engineering and technology. It was first awarded in 1989, initially as a bi-annual award, but now is awarded annually, with winners responsible for a wide range of engineering contributions. The prize is $500,000 and a medal (Figure 22). Those who knew Draper well think he would have been thrilled to have been a recipient of such a prize.

Figure 22. The Medallion Presented to Winners of the Draper Prize for Engineering.

CONCLUSION

Doc Draper was responsible for conceiving and leading the development of practical, reliable, and precise inertial guidance system technology. Starting from Missouri roots he pursued education in psychology, electrochemical engineering, and physics, all of which contributed to his success as an inventor and as an influencer of the national leadership that provided the resources to field the resulting technology. He also attracted students and staff with remarkable talents that leveraged and greatly expanded on Draper's concepts, enabling incredible engineering advances in aerospace guidance, navigation, and control over just a few decades. That technology and resulting systems helped turn the tide of the WWII battles in the Pacific in favor of the United States, enabled modern strategic defense systems, and was critical to the success of the Apollo program. In many ways, Draper rightfully earned the title of Father of Inertial Guidance. For that, he was widely recognized during his life for the those achievements (see the Appendix).

ACKNOWLEDGMENTS

The material presented in this paper and its interpretation is the responsibility of the author alone. However, it also must be noted that Ingrid (Drew) Crete was invaluable as a source of all raw material about Doc Draper used in the paper. She helped to systematically sift through many documents and artifacts from Doc's archives at the Charles Stark Draper Laboratory and to find relevant historical photographs. Her contributions were essential to timely completion of this presentation of Doc Draper's history.

Note that any figures not explicitly tagged as coming from a reference were acquired from the archives of the Charles Stark Draper Laboratory, Inc.

APPENDIX: SOME OF DRAPER'S ACCOLADES[10]

1946 Medal of Merit, Naval Ordnance Development Award
Sylvanus Albert Reed Award, Institute of the Aeronautical Sciences
1947 New England Award of the Engineering Societies of New England
1951 Exceptional Civilian Service Award of the Department of the Air Force
1955 43rd Wilbur Wright Memorial Lectureship of the Royal Aeronautical Society
1957 Navy Distinguished Public Service Award
Thurlow Award, the Institute of Navigation
Holley Medal, American Society of Mechanical Engineers
1958 Honorary Fellowship, Institute of the Aeronautical Sciences
Blandy Medal, American Ordnance Association
1959 William Proctor Prize of the Scientific Research Society of America
1960 U.S. Air Force Exceptional Service Award
Potts Medal of the Franklin Institute
1961 Navy Distinguished Public Service Award
1962 Space Flight Award, American Astronautical Society
Louis W. Hill Space Transportation Award, American Institute of Aeronautics and Astronautics
1964 The Commander's Award, Ballistic Systems Division, US Air Force
1965 National Medal of Science, a Presidential Award
1966 Wright Brothers Lecture, American Institute of Aeronautics and Astronautics
Vincent Bendix Award, American Society for Engineering Education
1967 Daniel Guggenheim Award
Distinguished Public Service Award, NASA
1968 Exceptional Civilian Service Award, US Air Force

1969 Public Service Award, NASA
Exceptional Civilian Service Award, U.S. Air Force
1970 Founders Medal, National Academy of Engineering
Distinguished Civilian Service Medal, Department of Defense
1971 W. Randolph Lovelace, II Award, American Astronautical Society
Rufus Oldenburger Award, American Society of Mechanical Engineers
1972 Lamme Medal Award, Institute of Electrical and Electronics Engineers
1974 Kelvin Gold Medal Award, Institution of Civil Engineers, London, England
1976 Inducted into the International Space Hall of Fame
1977 Allan D. Emil Memorial Award of the International Astronautical Federation
1978 Dr. Robert H. Goddard Trophy, National Space Club
Pioneer Award, Institute of Electrical and Electronics Engineers
1979 Inducted into the French Academy of Sciences
1980 Eagle Award for the Advancement of Astronautics, American Astronautical Society
1981 Elected into the National Inventors Hall of Fame
Langley Medal, Smithsonian Institution
Control Heritage Award, American Automatic Control Council
Enshrined in the Aviation Hall of Fame

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