DRAPER

50 Years as an Independent Engineering Innovation Nonprofit

90 Years of Outstanding Innovations and Service to the Nation

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TABLE OF CONTENTS

Message from our President & CEO

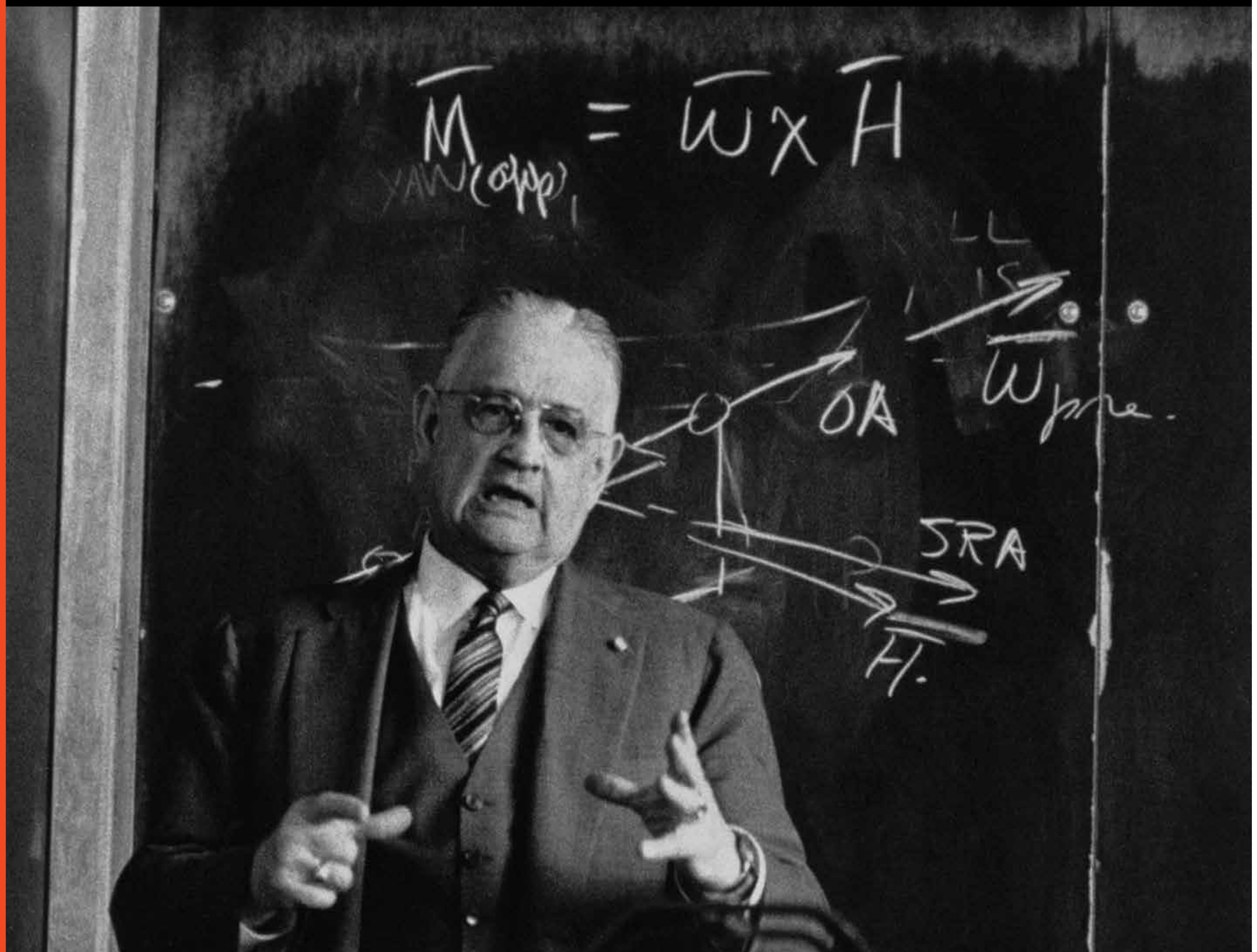
Fifty years ago, Draper took a monumental step in our historic legacy to carve out a new path for our organization's future. We proudly established ourselves as an independent nonprofit engineering innovation company dedicated to serving the nation's interest. Building on the legacy of Charles Stark "Doc" Draper, we innovated for our customers, enabling them to fulfill their missions, and in time established Draper as a leader in the design, development, and deployment of advanced technological solutions for the world's most challenging and important problems.

From inception to the present day, Draper's guidance and control solutions help NASA explore space and support our nation with credible strategic deterrence. Simply put, Draper's innovations are legendary. Overcoming our customers' challenges, Draper has found the way to deliver first-of-a-kind solutions and thought leadership in support of national security. This book is a testament to the amazing achievements over our 90 years as a laboratory and 50 years as a standalone nonprofit.

While our list of achievements is impressive, we're not relying on past accomplishments to define our future. As forward-thinkers, we have embarked on a transformation called Draper NXT to modernize and resource this legendary laboratory to provide exponential impact to our customers' missions while ensuring good stewardship of customer investments for decades to come. From the depths of the ocean to the farthest reaches of space, Draper is ready to find a way to solve our customers' most epic challenges. National security is our mission, and we have the talent and technology to continue Doc Draper's legacy for the next 50 years and beyond.

JERRY M. WOHLETZ

CHAPTER 1



Doc Draper teaching: The equation on the blackboard is an expression of gyroscope precession and applies to the single-degree-of-freedom gyro that Doc developed to a very high performance.

Origins: Charles Stark Draper

THE BIRTH OF THE LABORATORY AND REVOLUTIONIZING FIRE CONTROL

> *In any assessment of the importance of individual contribution to national defense, we cannot but think of von Neumann and the bomb; Rickover and the atomic submarine; and Schriever and the management of the ICBM program. But no person has so clearly dominated in engineering science as has Draper in automatic control and guidance.*
>
> - General L.I. Davis, USAF, 1963

Charles Stark Draper was the 20th century's key figure in developing and applying inertial navigation. He did more than any other individual to make inertial guidance practical. "I've been accused of being both the mother and father of inertial navigation," he once joked. The press called him "Mr. Gyro," but the staff at the Laboratory referred to him simply as "Doc." The story of Draper and the beginnings of Draper Laboratory are, in many ways, one.

The world was changing rapidly during the Laboratory's early years in the 1930s, and World War II was imminent. Doc Draper and his laboratory responded quickly to the war's demands and to the Cold War that followed. Throughout his five-decade career, Doc used his salesmanship and the Laboratory's technical skills to win new contracts and see them to completion. He forever changed the concept of the engineering research lab, combining the genius of the inventor, the savvy of the developer, and the fire of the educator to lead his laboratory into the real world, where development mattered as much as research, and accountability meant the difference between success and failure.

Over the years, the Laboratory pioneered the development of gyros and accelerometers with the precision necessary to use them for the inertial guidance of vehicles.

PUBLIC LEGACY: FROM MIT TO THE WORLD STAGE

Doc Draper was an entertaining lecturer and a colorful presence at MIT. He called his laboratory "an Athenian democracy, where talent ruled." He fostered discussion and debate among his staff and listened carefully to all sides of each issue, sensing that a better solution would evolve out of the process. But as Robert Duffy, former President of Draper Laboratory (1973-87), noted, "If it wasn't Doc's preferred solution, it didn't always survive. He could be ruthless."

Doc's picture appeared on the cover of Time magazine on January 2, 1961. That and his work on the Apollo mission helped make him a public figure. His reputation continued to grow until the late 1960s when campus unrest began at MIT in protest against the Vietnam War, focusing on the Institute's role in developing military weapons. These events led to the renaming of the Laboratory as The Charles Stark Draper Laboratory, a Division of MIT, and finally to the Lab's divestiture from MIT in 1973. Doc Draper was "retired" as head of the Laboratory in 1970, but the scrappy Draper immediately told the *New York Times*, "I was fired."

Draper was later reinstated and remained an important presence at the Laboratory until his death in 1987 at the age of 85. During his career, he received more than 75 awards, including election to the National Academy of Sciences, the National Academy of Engineering, and the French Academy of Sciences, and induction into the National Inventors Hall of Fame.

He ultimately will be remembered as much for his contributions to engineering education as for his applications of inertial navigation. He counted among his students some of the most famous names in aviation and space, and these included leaders in industry, the military and academia.

The Mark 14 gunsight 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.

- David Mindell, Dibner Professor, MIT
History of Engineering & Manufacturing, and Aeronautics & Astronautics

Born in Windsor, Missouri, on October 2, 1901, Doc Draper grew up with a love of planes and automobiles. In 1922, he graduated from Stanford University with a degree in psychology and then enrolled at MIT. According to his son James Draper, Doc said, "After graduating from Stanford, a friend and I drove east to look at Harvard. To get there from the Boston Post Road, we turned onto Mass. Ave. to pass over the Harvard Bridge. In those days, the decking was of planks so driving over it was rather like playing a xylophone. Approaching Harvard this way brought the then-new great gray pile of MIT, looming over the river, right before one's sight. We wondered what the place was; stopped outside the 77 Mass. Ave. entrance and inquired. I enrolled. My friend proceeded on to Harvard."

Four years later, he received a bachelor's degree in electrochemical engineering and was commissioned as a Second Lieutenant in the U.S. Army Air Corps Reserve. Sent to Brooks Field, Texas, for flight training, he failed to qualify as a pilot but was not dissuaded from flying and obtained a private pilot's license along with an airplane that he purchased. His experience and interest led to a fascination with the possibility of flying by instruments, a passion that would direct the course of his life.

After working for a year in a commercial research laboratory, he returned to MIT under a Crane Research Fellowship in Automotive Engineering to study fuel flame spectroscopy, but shifted to the study of engine noises.

He received a master's degree in 1928. With his fellowship renewed, he continued research on engine noise within the Internal Combustion Engine Laboratory as a doctoral candidate in physics. While still a Research Associate in the Engine Lab, he was asked in 1930 to teach a course in aircraft instruments when a faculty instructor left MIT. He accepted. In the fall, he began teaching and worked out of a corner room in the Engine Laboratory that he soon set up as his own laboratory:

> *Anybody who wanted to do anything could get lab space. The one thing there wasn't any of, and you didn't waste any time trying to get any of it, was money. So all the stuff I made, I got out of some automobile junkyard. I had a whole instrumentation laboratory...made up entirely out of stuff that cost nothing. I even bought the machine tools that we used to make the parts.*

He was appointed Assistant Professor of Aeronautical Engineering in 1935 and earned his Sc.D. in physics in 1938, at which time he was appointed an Associate Professor. According to legend, Doc held the distinction of having taken more courses for credit than anyone else in the history of MIT. He was appointed a Full Professor in 1939, and in 1951 he became Head of the Department of Aeronautical Engineering.

Doc Draper demonstrates a 40-mm gun director.

MARK 14 GUNSIGHT: THE SHOEBOX THAT REVOLUTIONIZED FIRE CONTROL

In 1933, Jerome Hunsaker, who had previously established at MIT the first formal course in aeronautical engineering in the U.S., returned to head the Department of Mechanical Engineering, where the aeronautical engineering course then resided. His close ties with the U.S. Navy brought in research contracts and led to the establishment of a joint program with the Navy's Bureau of Aeronautics in 1934 to develop instruments to study vibration in aircraft and their engines. Doc soon found himself designing a series of instruments for investigating engine and propeller vibrations.

Under Doc's leadership, the Aeronautical Instrument Laboratory—mentioned for the first time in the MIT President's Report for 1933-34—had "made notable contributions to the field and was attracting wide attention," according to Hunsaker's entry.

The Navy-funded research led to the successful development of a vibration measurement device that MIT licensed to the Sperry Gyroscope Company for commercial development in 1936 and, under this agreement, Doc became a consultant to Sperry. This relationship would have a profound impact on Doc's career as it brought him into close contact with Elmer Sperry, Jr., and his company—a key supplier of aircraft instruments and gyroscopes for military and civilian use.

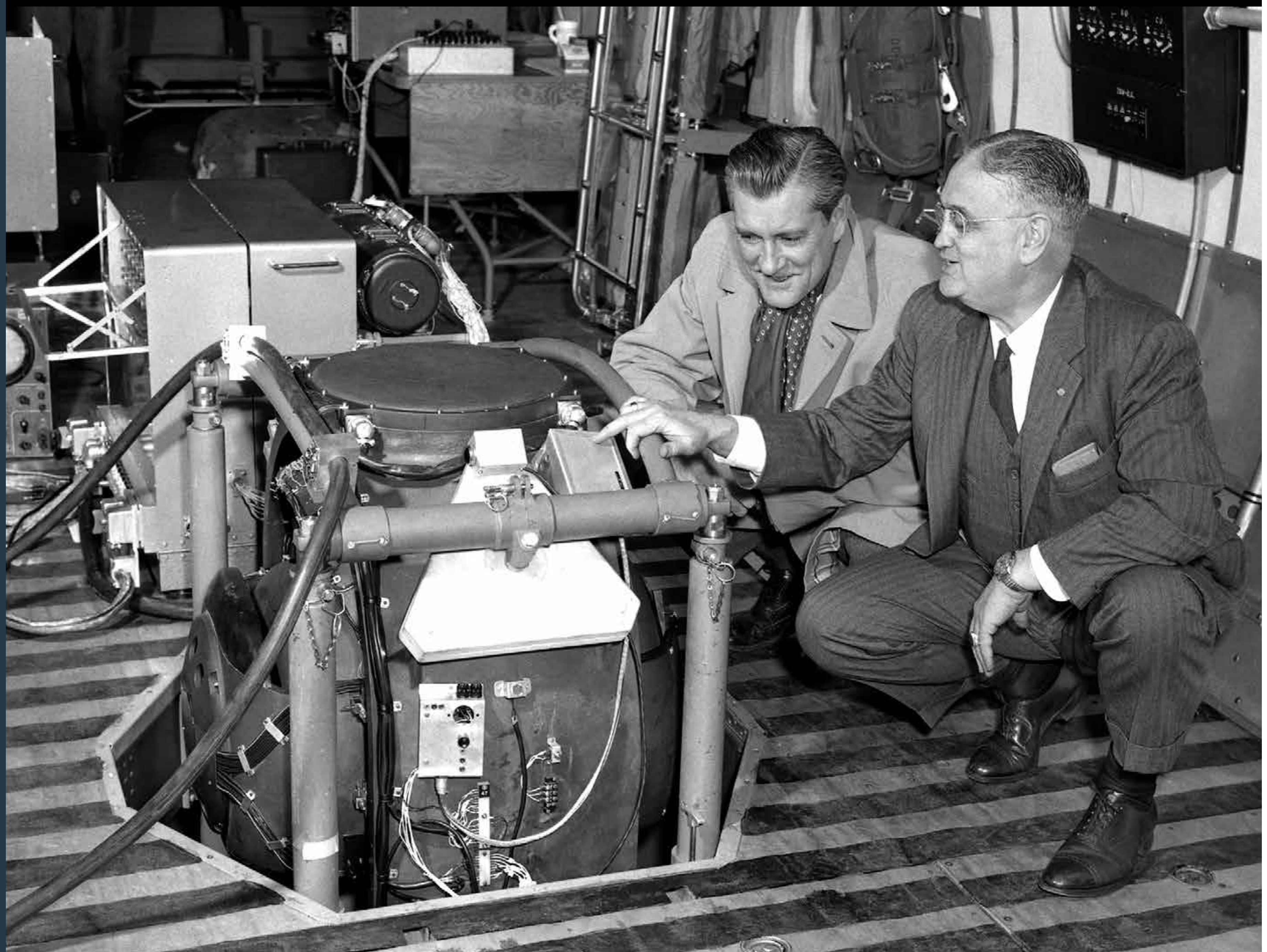
Doc's early success with the Mark 14 gunsight was a direct outgrowth of his deep interest in gyroscopic instruments and his work with the Sperry Company investigating the application of his rate-of-turn indicator to a lead-computing gunsight.

The gunsight was developed by the Laboratory under contract to the Navy during World War II. First used in the Pacific during the carrier battles of 1942, it enabled anti-aircraft gunners to shoot down numerous Japanese attack aircraft.

The Mark 14 was called "Doc's shoebox" because the experimental model was shaped like a rectangular box. It was designed to work while mounted on a gun on the deck of a rolling ship. It was the first of Doc's designs that used the "disturbed-line-of-sight" principle. The gyros, springs, and linkages of the Mark 14 caused the optics to "disturb" the line of sight so that the gun operator, while tracking the target, would actually be pointing the gun at the target's future location, where the bullet would later arrive. The Mark 14 brought the art of gunnery to an unheard level of effectiveness under battle conditions. It helped turn the tide of the war in the Pacific Theater. *The Boston Herald American* later remarked that the Mark 14 gunsight had "saved countless thousands of American lives." Another glowing World War II newspaper headline read, "Wizard MIT Gyro Gunsight Ends (Enemy) Air Mastery Over Sea."

At the conclusion of World War II, the Laboratory continued to design gun fire control systems using the disturbed-line-of-sight approach for both the Navy and the Army Air Corps.

(CHAPTER 2)



Doc Draper with CBS TV's Eric Sevareid discussing the historic SPIRE flight. The story aired on the science program Conquest in 1958.

Inertial Navigation Becomes a Reality

"ASTRONOMY IN A CLOSET" ADVANCES NAVIGATION WITHOUT STELLAR TRACKING

Doc Draper's flying experiences led to an interest in aerial navigation and aircraft instrumentation. Many of the latter devices became topics of study for Doc and his students, whose first task was to establish the theoretical background behind their operation. Once they had this understanding, they could attempt to engineer improvements, as was the case with Doc's rate-of-turn indicator, a gyroscopic instrument that indicates the standard rate-of-turn used by pilots when turning or banking and when visual contact with the ground is not available.

But inertial navigation—the idea that one could build a self-contained device within the enclosed confines of an aircraft to provide accurate position data—was beyond the technology available in the 1930s, when Doc became interested in the theory and mechanics behind this revolutionary idea. He was fortunate, however, in having a few well-qualified graduate students who could undertake studies of what Doc described as the "closed-box navigation situation" as part of the theoretical work required for their graduate theses.

One of these students was Walter Wrigley. In 1940, the two men produced a paper describing an accelerometer—an electromechanical device that measures g-force acceleration and is required for an inertial navigation system. Under Doc's direction, Wrigley began an investigation into the physical nature of the accelerations affecting a moving vertical. Wrigley's dissertation, A*n Investigation of Methods Available for Indicating the Direction of the Vertical from a Moving Base*, completed in 1941, laid the theoretical foundations for inertial navigation. But it would be several years before the technical advances brought about by World War II opened the door for its potential utilization.

Dave Hoag (right) and Ralph Ragan examine Polaris hardware.

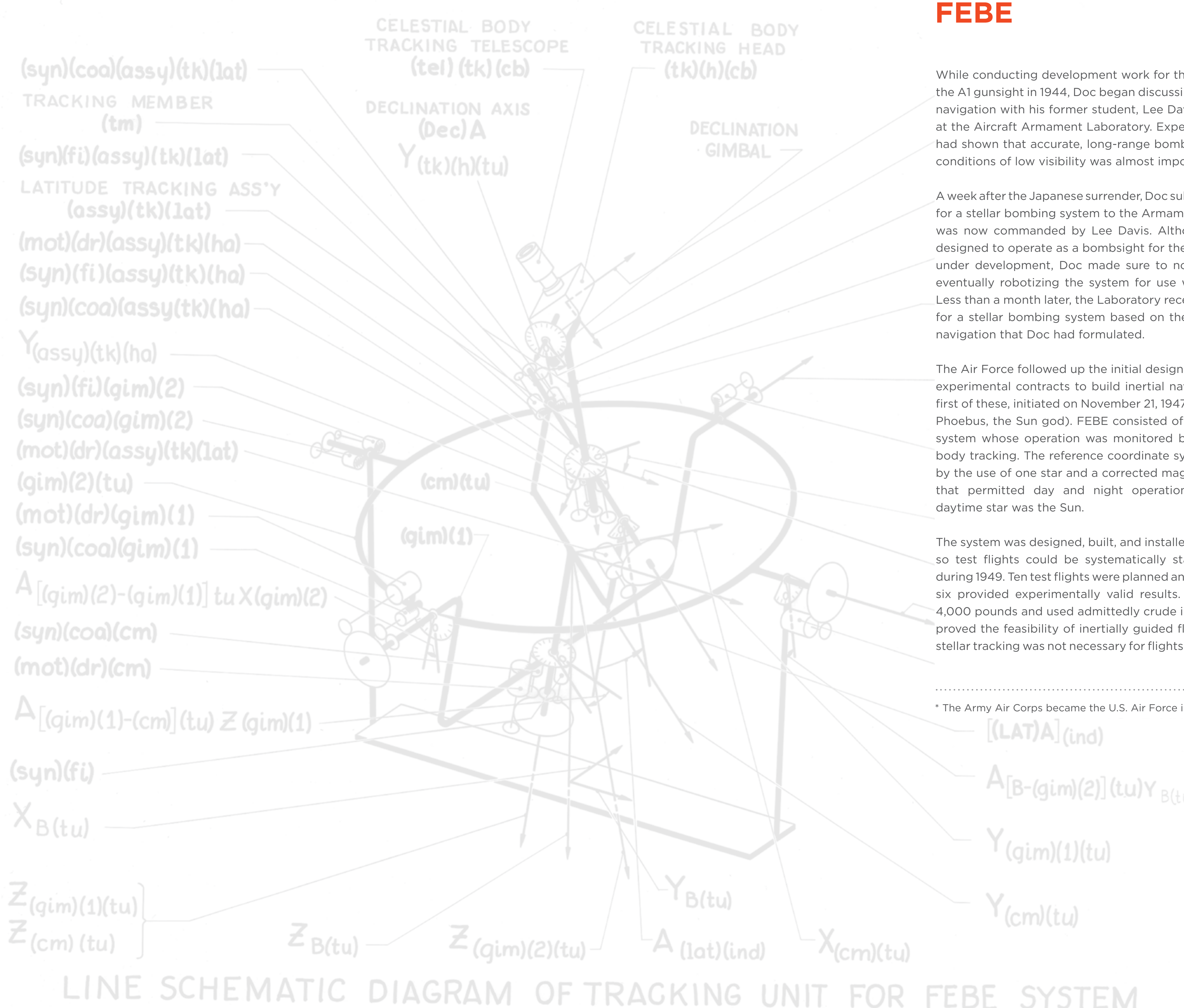
THE ABCs OF INERTIAL SYSTEMS

Inertial navigation was Doc's answer to how one could fly a plane autonomously over long distances without seeing the ground and without relying on measurement help from the ground. As he once put it, an inertial system does for geometry—angles, distance, and speed—what a watch does for time.

Motivated by Doc's incentive and drive, the Laboratory developed the necessary precision accelerometers and gyros and applied them to the inertial guidance of vehicles. In these systems, the gyros measure changes in vehicle direction or orientation; the accelerometers measure changes in vehicle velocity.

The accelerometers sense these velocity changes in much the same way a blindfolded passenger senses the acceleration, braking, and turning of an automobile—but with much greater accuracy. Similarly, the gyros can sense changes only in direction and orientation. The initial value of these parameters must be obtained by some other source.

Accelerometers and gyros make their measurements while self-contained in a local inertial frame and require no physical or electromagnetic contact with external references. This inspired Doc's characterization of inertial navigation as "astronomy in a closet." Practical inertial systems demand extremely accurate instruments. The development of such accelerometers and gyroscopes is one of the Laboratory's most renowned successes. However, even tiny errors in these instruments can, in time, cause the system-indicated attitude, velocity, and position to drift away from the truth in the same way that a clock drifts. For longer missions, they must be periodically reset or corrected.



FEBE

While conducting development work for the Army Air Corps* on the A1 gunsight in 1944, Doc began discussing his ideas on inertial navigation with his former student, Lee Davis, and the engineers at the Aircraft Armament Laboratory. Experience during the war had shown that accurate, long-range bombing at night or under conditions of low visibility was almost impossible to achieve.

A week after the Japanese surrender, Doc submitted specifications for a stellar bombing system to the Armament Laboratory, which was now commanded by Lee Davis. Although the system was designed to operate as a bombsight for the jet-propelled aircraft under development, Doc made sure to note the "possibility of eventually robotizing the system for use with guided missiles." Less than a month later, the Laboratory received a study contract for a stellar bombing system based on the principles of inertial navigation that Doc had formulated.

The Air Force followed up the initial design study with a series of experimental contracts to build inertial navigation systems. The first of these, initiated on November 21, 1947, was called FEBE (for Phoebus, the Sun god). FEBE consisted of an inertial navigation system whose operation was monitored by means of celestial-body tracking. The reference coordinate system was established by the use of one star and a corrected magnetic azimuth system that permitted day and night operation, provided that the daytime star was the Sun.

The system was designed, built, and installed in an Air Force B-29 so test flights could be systematically started and completed during 1949. Ten test flights were planned and completed, of which six provided experimentally valid results. Although it weighed 4,000 pounds and used admittedly crude instrumentation, FEBE proved the feasibility of inertially guided flight and showed that stellar tracking was not necessary for flights of moderate duration.

* The Army Air Corps became the U.S. Air Force in September 1947.

SPIRE guides the first coast-to-coast flight without the aid of a pilot.

SPACE INERTIAL REFERENCE EQUIPMENT (SPIRE)

Before the FEBE program was completed, the Laboratory began preliminary design work on a more-advanced inertial bombing system for the Air Force code named SPIRE. The system was intended for use in long-range, high-speed bombers. Doc expected the new system to achieve a circular error probable* (CEP) of about 1 nautical mile (nmi) in a 10-hour flight to the target. To accomplish this goal, the Laboratory developed a new series of improved gyros and accelerometers based on the floated gyro concept. Unlike FEBE, SPIRE would be purely inertial: there was no celestial tracker. Active work on the system began in September 1950.

As no star trackers were employed, the basic reference coordinate system was established by means of three single-degree-of-freedom (DOF) gyros. An analog computer was employed to convert the inertial coordinate system established by the gyros to an Earth-referenced great circle coordinate system. The hardware consisted of a large gimbaled unit containing the inertial platform using model 45 FG gyros and model 125 FP accelerometers. A large electronic console was used along with associated equipment such as the navigation instrument panel and a pilot's panel. No attempt at miniaturization was made in either the mechanical or electrical portions of the system. The system was assembled and installed on a B-29 on loan from the Air Force in January 1953. It was given a 1-hour shakedown flight on February 6.

* Circular error probable is a measure of a system's precision. It is defined as the radius of a circle, centered around the mean, whose boundary is expected to include the landing points of 50% of the rounds.

The next day, Doc told Chip Collins, the Laboratory chief test pilot, to ready the B-29 to perform a coast-to-coast test of the SPIRE system. The official purpose of the flight from Bedford, Massachusetts, to Los Angeles, California, was to test the performance of the navigation system and its interaction with the autopilot over an extended flight track. To Doc, the flight was intended to be his proof-of-concept to the naysayers. He would prove them wrong by presenting the test results of the flight at a symposium on inertial navigation scheduled for the following morning in Los Angeles.

Among the team who accompanied Doc on the flight was SPIRE's designer, Roger Woodbury. Together, the two of them mapped out the flight plan to scale on a long roll of paper, showing the intended course and the actual course flown. Conditions throughout the flight were relatively stable until the B-29 began to fly over the Rockies. Collins relates what happened next:

> *We were in dense cloud cover somewhere west of Denver when suddenly we encountered some air turbulence accompanied by the displacement of the rudder, thereby driving the airplane into a right turn. Doc, Roger Woodbury, and the rest of them in the back of the plane couldn't see what was happening to the rudder. They couldn't even see outside.*
>
> *What was apparent to them was the gimbal was turning with respect to the aircraft. There was some panic in the back, but Doc and Roger Woodbury remained calm. Doc asked me what was going on, and I told him I was getting a hard correction to the right. Once we broke out of the cloud cover, we all began hunting for landmarks and tuning radios toward the coast to determine our current position. It was unbelievable, we were still on course. I couldn't figure out how that could be when we changed heading almost 35 degrees.*
>
> *Upon landing, we learned that a weather front had developed causing a wind shift and that the SPIRE system had detected the change and automatically corrected the autopilot to stay on course. This was delightful news to Doc because it was exactly what the system was supposed to do.*
>
> *That night, the Draper team stayed up late, plotting the test results so they could be presented at the symposium. The next morning, we all went to UCLA where industry presenters were scheduled to discuss the possibility of total inertial flight. Doc got up there and said we had just done it, and here was the evidence showing them the track chart. 'The accuracy,' he said, 'wasn't very good. We were off a few miles.'*
>
> *There were audible gasps in the audience. People just couldn't believe it had been done.*

Having successfully demonstrated the feasibility of inertially guided flight, Doc's laboratory set out to design a system that weighed less than 1,500 lb—half the weight of SPIRE—that could indicate aircraft position to within 2 nmi after 10 hours of flight. This was SPIRE Jr., which was based on the concepts proved by SPIRE but oriented more toward operational requirements. Flight testing began in November 1957 and continued through July 1958.

SPIRE Jr. incorporated a number of features that later came into general use on ICBM guidance systems. Its shell gimbal design was subsequently used in the Titan II guidance system, and its pendulous integrating gyro accelerometer (PIGA) became the forerunner of the 25 PIGA and 16 PIGA accelerometers used in the ICBM guidance systems later developed by the Laboratory.

It was truly one of our finest hours and marked the true beginning of inertial system guidance.

- Chip Collins talking about the first SPIRE flight.

Chief Test Pilot Chip Collins (right) and co-pilot Dave Buxton review flight path prior to a SPIRE Jr. test flight in 1958.

SUBMARINE INERTIAL NAVIGATION SYSTEM (SINS)

A few months after FEBE was initiated, the Navy's Bureau of Ordnance asked the Laboratory to provide a proposal to undertake the development of a more accurate stable element for shipboard use that would be based on the Laboratory's work on the development of inertial platforms. Although the contract for the project, code named MAST (MArine STabilized platform), was issued on September 3, 1948, design and construction was deferred until the spring of 1950 to take advantage of the lessons learned from FEBE and the Gunar fire control system (a self-contained system incorporated in the gun mount) also being developed for the Navy.

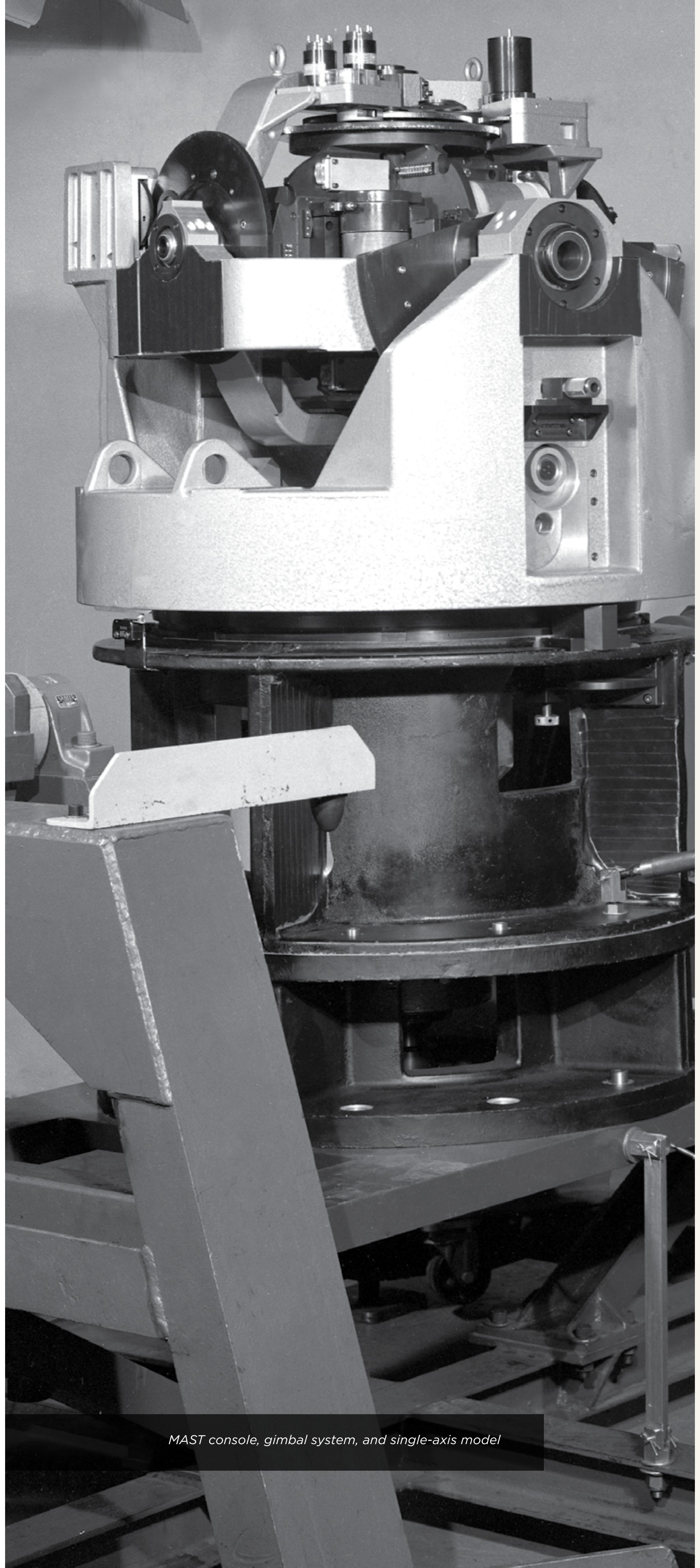
While the Laboratory was working on MAST—it would not be successfully tested at sea until March 1954—Doc was approached by personnel from the Office of Naval Research to discuss the feasibility of using inertial navigation for guiding submerged submarines. As a result of these discussions, the Office of Naval Research issued a one-year contract (later extended) in 1950 for a study of inertial navigation applied to the "problems of submerged performance." What emerged from this work were two reports prepared by John Hovorka under the supervision of Assistant Laboratory Director Forrest E. Houston. The first report, *Theoretical Background of Inertial Navigation for Submarines*, issued in March 1951, addressed the fundamental approaches to the problem of using a stabilized platform to indicate a vertical reference. The second report, issued five months later, examined the practical application of such a system.

On the basis of this work, the Navy asked the Laboratory to construct a working model of a Submarine Inertial Navigation System (SINS). The first SINS designs were based on the MAST platform using instruments that originally were designed and constructed for SPIRE. The concepts and requirements involved in submarine inertial navigation were discussed with the Air Force officers at Wright Field, who gave permission to use instruments belonging to the Air Force that had not been required for SPIRE. Operating tests were carried out in the Laboratory in Cambridge and in a test van in which the SINS gimbal system was mounted. The first unit was installed on the Navy cargo ship Alcor in February 1955 and tested on a trip from Norfolk to Naples and back, as well as a trip from Norfolk to San Juan. Although good performance was demonstrated for as long as 108 hours, it was intermittent for many shorter periods. The need for improved gyros and accelerometers was evident, resulting in an effort to reduce drift rates and uncertainties in these components.

Doc was a firm believer in the single-DOF gyroscope and the elegant virtues of letting gyroscopes remain in fixed orientation in inertial space. But as the earth rotates and the submarine's position changes, the gyroscopes in the inertial navigation system are subject to a varying gravity field. The slightest imbalance to their rotors would cause significant errors over time. Achieving perfect or near-perfect balance was an exceedingly difficult task.

MK2 SINS, developed by the Autonetics Division of North American Aviation, was a local-level system kept horizontal at all times and aligned to cardinal headings. This local-level orientation permitted a simple set of mechanization equations, minimized adverse effects of accelerometer scale-factor errors, and allowed for a relatively easy readout of the boat's roll, pitch, and heading. After the Polaris program got underway, the U.S. Navy standardized on the Autonetics MK2 for SINS units for the submarines that would be needed to launch Polaris missiles.

In October 1959, Doc, who also was working on the guidance system for the Polaris missile, predicted that the "allowable uncertainty in the firing point position" for the submarines that were going to launch the next generation of Fleet Ballistic Missiles would have to be less than 0.025 mi to achieve the accuracy desired for the missile. He convinced the Navy to fund development of an improved system, the MK4 SINS, based on the nulling action of untorqued gyro units. The program started in 1960 and results from sea trials in 1964 were good, but the Navy decided to continue with the existing equipment.



MAST console, gimbal system, and single-axis model

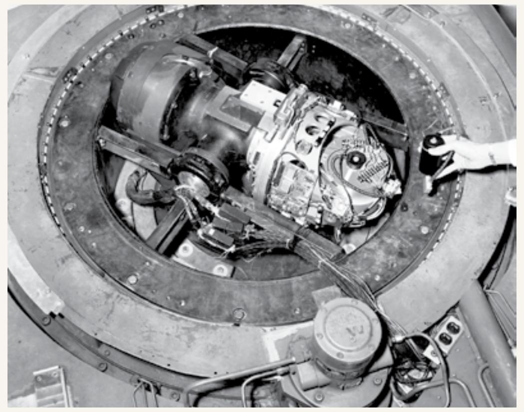
THE FLOATED GYRO

One of Doc's many advancements that would enable accurate inertial navigation was the development of the single-DOF floated gyro. This electromechanical device consisted of a spinning rotor within a cylindrical container. The container was mounted on an axle with ball bearings within another slightly larger container such that the rotor's spin axis was perpendicular to the axle. Due to the conservation of angular momentum, if the device were rotated about an axis orthogonal to both the spin axis and the axle (input axis), the inner container would react by trying to rotate about the axle (output axis).

Doc decided to "float" this inner container in a viscous fluid to relieve any frictional load from the axle bearings that might impede the angular motion. The fluid also dampened the inner container's reaction rate. By measuring the reaction angle of the inner cylinder relative to the outer cylinder about the output axis, one could infer what angular motion had been applied along the input axis.

Additionally, closed-loop control was applied to the inner cylinder using a torque motor, driven by the output axis signal, to keep the inner cylinder at null—or centered. This made the gyro a very precise, linear instrument whose torque motor current became the output signal. Over the decades, Draper engineers vastly improved on this basic gyro design by decreasing tolerance using precision machining, increasing rotor speed, improving the electronics, and decreasing its overall size.

The development of the Hermetic Integrating Gyro (HIG) was considered a landmark in the development of inertial navigation. *Time* magazine in its April 29, 1957, issue called it the "Instrumentation Laboratory's most important technological advance" in building the inertial navigation system that was destined to guide the first generation of ICBMs.



Hermetic Integrating Gyro

CHAPTER 3

Launch of the Mercury Atlas missile

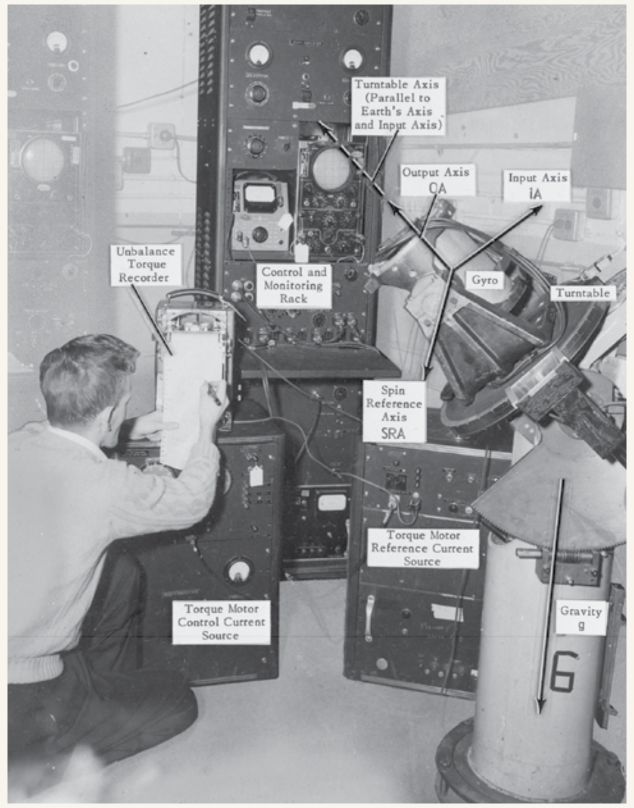
Guiding U.S. Air Force Ballistic Missiles

APPLYING INERTIAL GUIDANCE FOR STRATEGIC SYSTEMS

In October 1953, the U.S. Air Force tasked a select group of scientists under the chairmanship of John Von Neumann to review the Atlas Intercontinental Ballistic Missile (ICBM) program. The "Teapot Committee," as it was unofficially called, maintained very close relationships with experts in technology via their connections with the Scientific Advisory Board. Especially important among these was Doc Draper, whom one scientist described as knowing "more by far about the science and technology of inertial guidance than anyone else in the world."

Doc was already familiar with the program, having previously served on an earlier Atlas study committee. Because of the development of lighter, higher-yield nuclear weapons, the committee recommended that the stringent 1,500-ft accuracy requirement could be changed to 2–3 nmi. The less stringent accuracy requirement prompted the Teapot Committee to urge the study of an onboard, all-inertial guidance system. Doc Draper, always the technical optimist, insisted that he could do better than the originally specified accuracy requirement.

Two weeks after the Teapot Committee's report was issued, Convair, the prime contractor for Atlas, awarded Draper Laboratory a contract to investigate the feasibility of an ICBM inertial guidance system, assist in the design of the primary radio guidance system, and help engineer the post-boost vehicle attitude control system. This was the first step in establishing our long-standing role as the nation's premier center for the design and development of inertial guidance for strategic missiles.



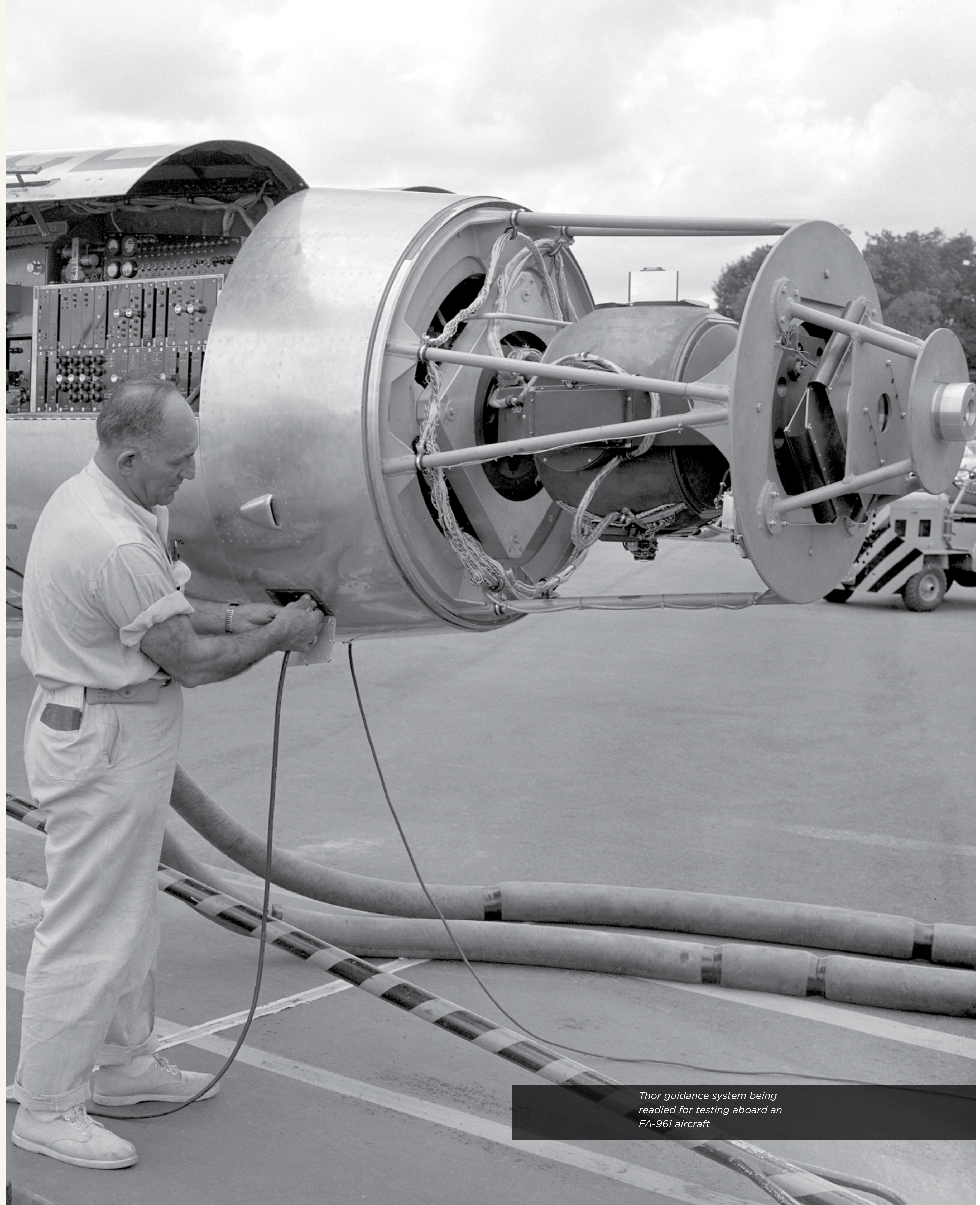
Gyro unit on gravity tumbling test bed connected on a restraint servo loop

Q-GUIDANCE

Dick Battin and Hal Laning were tasked with providing an analytical solution to the guidance problem for the Atlas program. With no standard methods in the literature to guide them, they invented a process called Delta Guidance based on the use of a Taylor series expansion to create a mathematical model for the trajectory of a ballistic missile. Though simple in concept, it was not easy to implement in early analog computers due to computational limitations. Nevertheless, they were determined to make their Delta Guidance approach work. However, during the summer of 1955 Battin visited Convair in San Diego and returned to Cambridge "with a new vocabulary" and a better understanding of the guidance problem. After debriefing Hal Laning, the two abandoned the Delta Guidance concept.

After several weeks of mulling over the problem, Hal Laning came up with an elegant solution based on a velocity-to-be-gained approach, in which engine thrust is applied in the direction needed to bring the vehicle back to the intended trajectory. Because the mathematics were based on the solution of a vector matrix equation where the key matrix variable was denoted by the symbol Q, it was named Q-Guidance. The Q-Guidance concept was presented to the inertial guidance committee at the first Technical Symposium on Ballistic Missiles held at the Ramo-Wooldridge Corporation in Los Angeles on June 22, 1956.

While the Q-Guidance algorithm was never implemented on the Atlas program, it did prove crucial for the Thor program. Thor was flown with inertial guidance using the Q-Guidance approach for the first time on December 19, 1957.



Thor guidance system being readied for testing aboard an FA-961 aircraft

THOR

Immediately after the Atlas program was underway, the Air Force initiated two additional missile programs: the Titan ICBM, which was a backup design in case Atlas failed, and Thor, an intermediate range ballistic missile (IRBM) with a range of 1,500 mi (~1,303 nmi). Thor was conceived as a stopgap measure that could be deployed rapidly to fill the perceived missile gap with the Soviet Union. Given its range and specified circular error probability (CEP) of 1 nmi, and given that weight was a critical factor, some stakeholders doubted that such a system could be produced within the Air Force's two-year time frame.

In an evening session with another of his former students, Doc convinced Lt. Col. Benjamin P. Blasingame* that the AC Spark Plug Division of General Motors—backed by Draper Laboratory—could do the job. With Blasingame's consent, the project went ahead with inertial guidance as the primary guidance system and used radio control as the backup system.

The guidance system, designed by Draper engineers and manufactured by AC Spark Plug, used a three-gyro-stabilized inertial platform to measure the missile's attitude, while three PIGA-type accelerometers measured acceleration. Using these measurements and the Q-Guidance approach, the onboard computer was able to determine what changes in the three-dimensional (3D) thrust vector were needed. These results were sent to an autopilot to keep the missile on its planned trajectory.

* Blasingame, head of the Air Force Western Development Division, received his D.Sc. degree from MIT in 1950; Doc Draper was his thesis advisor.

TITAN

Titan I, authorized in May 1955, was the first two-stage, liquid-fueled ICBM ordered by the Air Force. The plan was to use a radio guidance system until the inertial guidance system under development by Bosch Arma was successfully proven. Bosch Arma developed the first fire control systems. In 1958, the Air Force held a design competition to select a vendor to develop an advanced inertial guidance system for the missile. By then, Draper Laboratory had developed a prototype of what would become the Model 2-25 inertial platform, which served as the basis for AC Spark Plug's successful bid for the Thor guidance system. The new system was never deployed on Titan I, which depended on radio guidance when it was deployed in 1962. Titan II was based on a Draper prototype design and was tested successfully on July 25, 1961. In August 1962, the Defense Department announced that the Titan II guidance system would be modified for use in the Titan III rocket. The Titan III rocket provided an early, heavy-lift booster for Earth-orbiting payloads launched by the U.S. Space Program.

In addition to the Model 2-25 inertial platform, Draper engineers replaced Thor's analog computer with a digital computer for the Titan II guidance system. This approach, coupled with improvements in the gyros and accelerometers, yielded a CEP accuracy of roughly 0.65 nmi, comparable to the accuracy of Titan I with its radio guidance. A modified version of the guidance system used on Titan II, supplied by AC Spark Plug, was used successfully for Titan III.

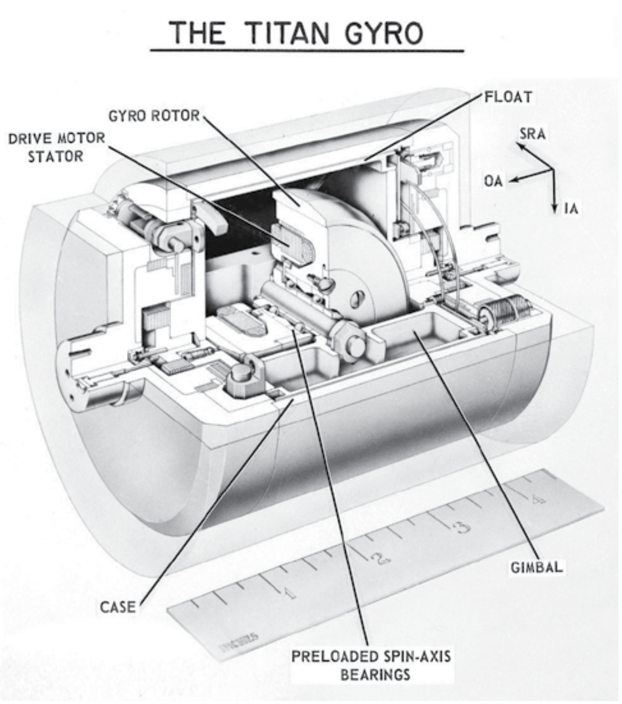
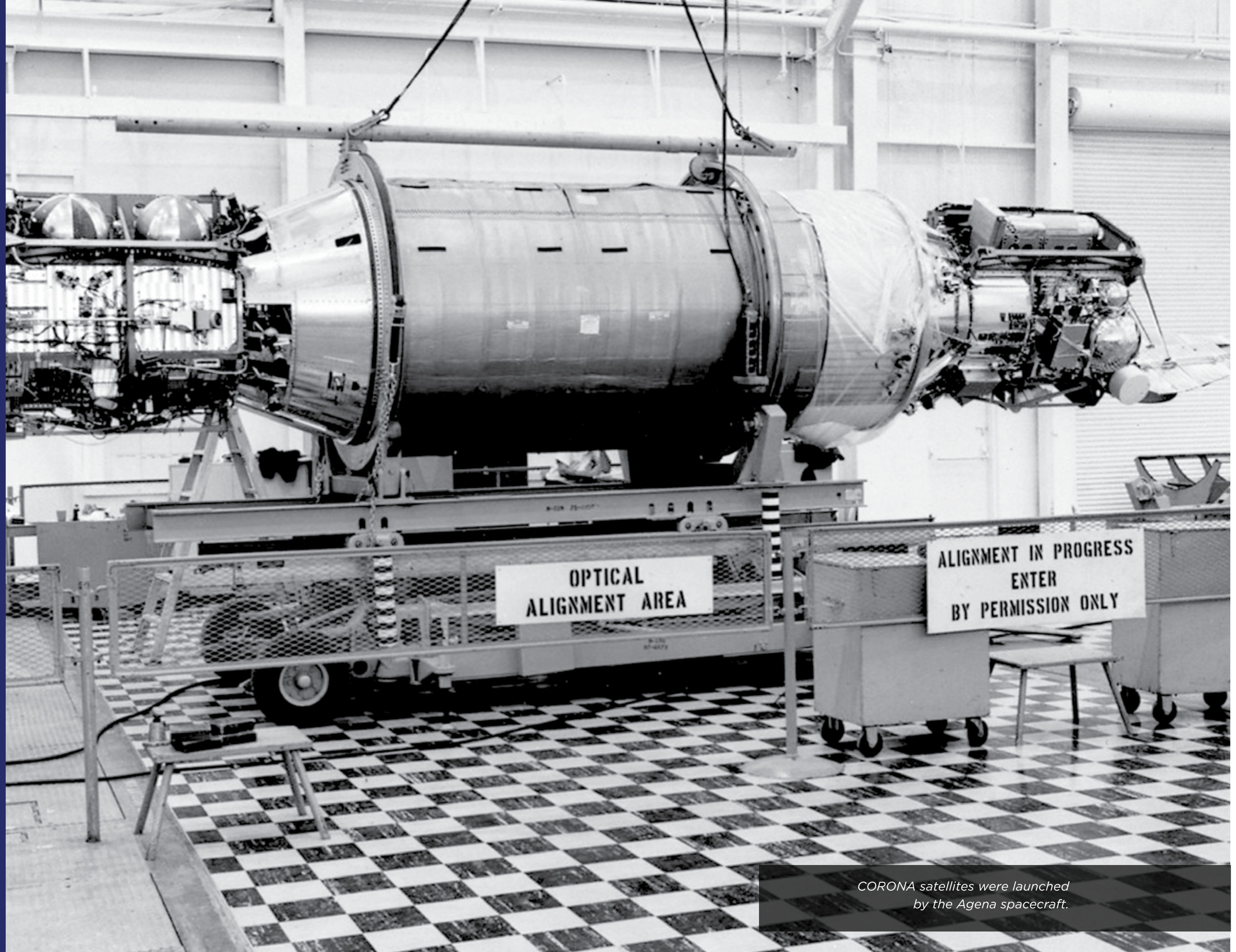


Illustration of the Titan gyroscope

The Titan II guidance system platform was based on a Draper prototype design and built by industry.



CORONA satellites were launched by the Agena spacecraft.

2005 DRAPER PRIZE FOR CORONA

The 2005 Draper prize was awarded to Minoru "Sam" Araki, Francis J. Madden, Edward A. Miller, James W. Plummer, and Don H. Schoessler for the design, development, and operation of CORONA, the first space-based Earth surveillance system. A heroic achievement, CORONA was executed within 16 months, with great national urgency and in extreme secrecy, by a multidisciplinary, multiorganizational engineering team:

- **Sam Araki** was the Lockheed lead engineer for the new gyro-stabilized spacecraft, which from Earth orbit had to serve as a stable platform for camera operation and position itself for recovery of the film capsule.
- **Francis Madden** was chief engineer of Itek Optical System's camera design group, whose team developed a panoramic camera that doubled the previous best focal length and improved image resolution.
- **Don Schoessler** led Kodak's film design and production team. Its newly invented, thin-based, polyester photographic film had to withstand temperature variations of 800°F and survive atmospheric radiation.
- **Edward Miller** of General Electric Co. was the lead developer of the satellite recovery vehicle — the first manmade object to return from Earth orbit.
- **James Plummer** was the CORONA Program Manager at Lockheed who led the engineering effort and its management process.

CORONA

CORONA was the code name for the highly classified program, conducted by the Central Intelligence Agency and the Air Force, that produced a series of satellites used for strategic photoreconnaissance from 1959-72. The program began in 1956 under the name Discoverer, part of the WS-117L satellite reconnaissance and protection program of the U.S. Air Force. CORONA's mission was accelerated following the shoot-down of a U-2 spy plane over the Soviet Union in May 1960.

Launched into near-polar orbit on U.S. Air Force Thor boosters, CORONA satellites took pictures of the Soviet Union, the People's Republic of China, and other areas while in orbit 100 mi above the Earth, and returned the exposed film in a capsule ejected from the spacecraft. The film was collected, processed, and used by the CIA.

Draper Laboratory's role in CORONA began early in 1955 when Air Force Capt. James S. Coolbaugh, an aeronautical engineer by training who oversaw the Air Force's first satellite program, learned that several reserve officers enrolled in the Air Force master's degree program at MIT were doing theses on satellite control systems. Coolbaugh suggested, and Doc agreed, that it would be to the Air Force's advantage to put the graduate students to work on Coolbaugh's project.

Lt. John C. Herther was one of these students. He and his roommate, Lt. William O. Covington, had researched the background material on the requirements for CORONA and were working on complementary theses evaluating spacecraft guidance and on-orbit control system concepts. Their theses proposed placing a satellite in a 300-mi orbit using an inertially referenced, computer-controlled, two-stage thruster fired at apogee. The satellite would use passive on-orbit gravity stabilization. These concepts eventually became the foundation for the ascent guidance and three-axis passive gravity gradient on-orbit stabilization used on the Lockheed Agena spacecraft that carried CORONA's photographic capsule.

When it came time for Lockheed to select a guidance and control system, Draper Laboratory had to contend with a competing proposal from North American Aviation's Autonetics Division, which had won the design of the guidance package for the Minuteman missile. Doc's reputation and the availability of Dr. Joe DeLisle as project engineer—he had been largely responsible for the success of SINS—gave the advantage to Draper Laboratory. DeLisle's expertise and our low-cost development approach were very attractive to the cash-strapped Air Force project office. DeLisle proposed that Draper Laboratory could reduce cost by scaling down the weight and performance of the inertial measurement unit (IMU) from the Sperry SINS system to meet the needs of the Agena/CORONA system. This approach would require only a small engineering staff.

The Air Force agreed and awarded a sole-source contract to Draper for the spacecraft guidance design and on-orbit control. Working on a shoestring budget, the team built the first few systems and issued progress report letters instead of formal written reports. The only documentation generated for the project consisted of the MIT master's theses, briefing aids, engineering drawings, and manufacturing data.

The guidance system had a three-axis IMU that used a pitch/yaw gimbaled engine to maintain the ascent trajectory plane, with gas jets for vehicle roll control. On orbit, three-axis stabilization for horizontal flight kept the camera axis pointed earthward to minimize blur from pitch, roll, and yaw cross-track motion. This maintained the diffraction-limited, static, high-resolution lens, film reconnaissance photography by using the pitch and roll gyros, which were updated continuously using infrared horizon sensors for determining the vertical to <0.1-deg accuracy.

During the operational life of the CORONA program, more than 140 successful missions delivered upward of 2.1 million feet of film to U.S. intelligence agencies. This imagery gave American leaders unprecedented insights into critical national threats, particularly from the Soviet Union.

> *The imagery [from CORONA] profoundly altered the course of the Cold War.*
>
> - Peter B. Teets, Director, National Reconnaissance Office, Remarks at the National Academy of Engineering's presentation of the Charles Stark Draper Prize to the CORONA team on February 21, 2005

Rocket sled test of MPMS/AIRS (circa 1980)

MINUTEMAN

As the Cold War heated up and the Titan program was well underway, the Air Force sought to improve the accuracy of its next-generation ICBM: the Minuteman II. In 1962, its Ballistic Systems Division directed that the Minuteman guidance contractor, Autonetics, replace the original accelerometers with Draper's more accurate accelerometer, the 16 Pendulous Integrating Gyro Accelerometer, Modification G (16 PIGA Mod G).

The Pendulous Integrating Gyro Accelerometer (PIGA) originated from the gyroscopic accelerometer designed by Dr. Fritz Mueller for the V-2 rocket, which was the world's first long-range guided ballistic missile used by Germany during WW II. The PIGA was later used by Wernher von Braun and his team at the Redstone Arsenal at Huntsville, Alabama. Doc Draper selected this integrating accelerometer as the foundation of the PIGA design because it was capable of measuring large velocities over the wide dynamic range associated with missile flight trajectories.

Draper transferred the PIGA design package to Autonetics for development and continued technical support to the Air Force and Autonetics. The 16 PIGA Mod G was used in Minuteman III, which was deployed in 1970. Responsibility for the design package was transferred back to Draper by mutual agreement among the Air Force, Autonetics (now Boeing), and Draper in 1998.

Today, Draper continues to support the Minuteman III sustainment program, with a focus on the 16 PIGA strategic sensor and associated test equipment. Minuteman III, the most responsive leg of the nuclear triad, remains on alert and is expected to continue in the inventory until at least 2035.

The 16 PIGA Mod G was used on Minuteman III, which was deployed in 1970.

KEY INNOVATIONS IN INERTIAL MEASUREMENT: THE FLIMBAL

In 1957, Draper began developing a new technology designed to eliminate the mechanical gimbals (three-axis mechanical pivot supports), which are used to decouple the motion of the vehicle from the stable platform on which the inertial instruments are mounted. In this new approach, the gyroscopes and accelerometers—along with their electronics—were enclosed in a sphere, which in turn was suspended at neutral buoyancy or "floated" in a fluorocarbon fluid within an outer sphere. This Floated Inertial Measurement Ball (FLIMBAL) kept the inner sphere in a stable orientation using feedback from the gyroscopes. Instead of using servo motors to drive gimbals, the stable platform orientation was maintained by three pairs of hydraulic thrust valves powered by a turbo pump at the center of the inner sphere. In this system, very precise temperature control was maintained by transfer of heat from the fluid that was pumped through heat exchangers on the outer sphere.

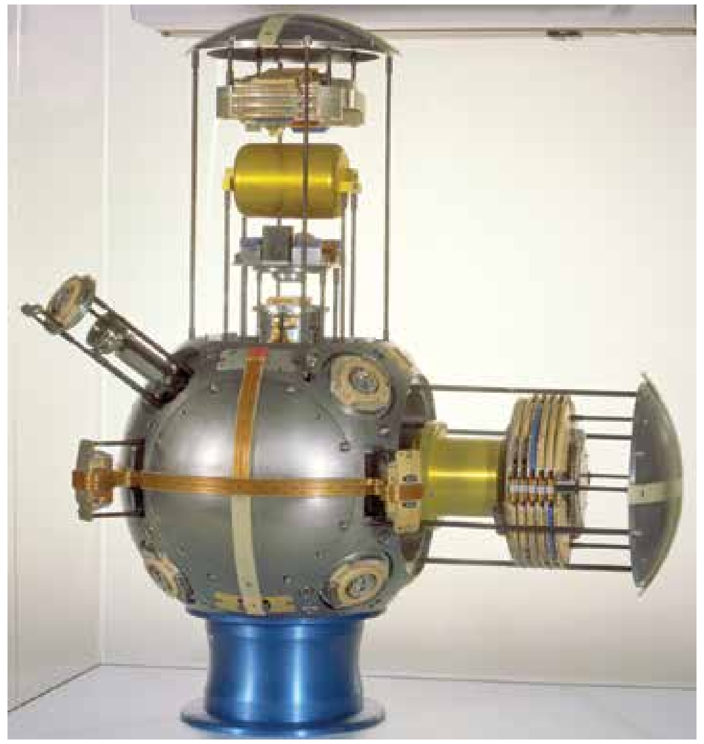
By eliminating the fan-blown gas used for cooling in traditionally designed inertial measurement units (IMUs), the FLIMBAL achieved a much more uniform thermal control, thereby reducing thermal-induced sensor errors. The FLIMBAL also allowed the IMU to be "all attitude"—able to launch in any direction—without the need for gimbals. This greatly improved the accuracy and the reaction time of the missile, as well as eliminated the risk of gimbal lock.

Following the development of a very simple proof-of-concept in 1962, the Air Force sponsored the development of SABRE, a system designed to self-align and guide the missile during both the boost and reentry stages. SABRE employed gyro-compassing as well as leveling using the 16 PIGA measurements, thus making it a true "black box" inertial reference—meaning it needed no outside references beyond the Earth's gravity and rotational spin. SABRE was considered as a guidance option for Minuteman III, and both Autonetics and AC Delco successfully built copies using Draper drawings and support to demonstrate producibility.

Although never deployed, SABRE paved the way for improving the accuracy and alert readiness of Minuteman III by demonstrating that gyro-compassing could eliminate the Minuteman II autocollimators and bubble levels, which were both susceptible to seismic, nuclear, and other external environments. The SABRE program ended with a final successful 100-g centrifuge test.

In the early 1970s, the Air Force funded the Missile Performance Measurement System (MPMS)/Advanced Inertial Reference Sphere (AIRS),* which would demonstrate Draper's FLIMBAL capability using the latest third-generation inertial instruments. In July 1976, the MPMS/AIRS flew piggyback as an instrumentation package on a Minuteman III missile.

*Also referred to as the Advanced Inertial Reference System.



AIRS FLIMBAL guidance system

The Air Force selected the Draper-developed AIRS design as the inertial measurement unit for its Peacekeeper missile.

PEACEKEEPER

In the 1970s, the Air Force began developing a new ICBM with improved accuracy over Minuteman. This new missile needed to carry an increased payload of up to 10 multiple independently targeted reentry vehicle (MIRV) warheads. Originally dubbed the MX, the high accuracy and large payload capability enabled its use as a counterforce weapon to destroy opponents' nuclear forces. Later named Peacekeeper by President Ronald Reagan, the MX had its first flight in 1983 and achieved initial operational capability in 1986, with full operational capability demonstrated in 1988.

At the heart of the Peacekeeper guidance system was a unique IMU designed by Draper Laboratory based on its FLIMBAL innovations. The inertial instruments were the extremely accurate Third-Generation Gyroscope (TGG), originally developed under NASA sponsorship for the Lincoln (Laboratory) Experimental Satellites (LES 8/9), and the Specific Force Integrating Receiver (SFIR), the next evolutionary step in the PIGA lineage. Both the TGG and SFIR benefitted from Draper's continued focus on improved materials, precise design, and improved fabrication techniques. Detailed modeling of the instruments using more capable computers also provided improved accuracy.

MPMS/AIRS was designed to be radiation hardened (rad hard), and in 1975 the Air Force contracted Draper to update the AIRS drawing package to meet MX radiation requirements. In 1977, Northrop won the MX AIRS IMU production contract, and the Draper-developed AIRS design was transferred to Northrop, which took the AIRS through advanced development into full-scale engineering development, and ultimately into production. During this time, Draper provided extensive mentoring, support, and monitoring of Northrop. Under contract with the Ballistic Missile Office, Draper continued as the Design Agent for the TGG and SFIR inertial instruments. We also continued to provide technical support for the AIRS, which included semi-real-time monitoring of on-alert missiles.

The technology evolution of the strategic grade instruments and their application in previous Air Force and NASA programs led to the successful development of the Peacekeeper missile. Peacekeeper is known for its high degree of accuracy, attributed to Draper's FLIMBAL innovations.

Peacekeeper third-generation inertial instruments: TGG and the SFIR

LGM-118A Peacekeeper

TRANSITIONING OUT OF THE COLD WAR

In 1983, President Reagan established the Commission on Strategic Forces (The Scowcroft Commission) to review the Strategic Modernization Program. Among its findings, the Commission recommended the design of a new Small ICBM with a single warhead that would be deployed on a rad-hard mobile launcher.

The baseline IMU was to be the AIRS, with modifications to make it lighter. Because deploying a single reentry vehicle takes less time than deploying multiple bodies, the new design could eliminate some in-flight cooling equipment, thus reducing size, weight, and power needs. The new system was named Mod AIRS, and Draper provide technical support to this system while also continuing to support the Peacekeeper program.

In parallel with the Mod AIRS, the Air Force created a program to develop an Alternate Inertial Navigation System (AINS) to improve cost and performance competitiveness. GE, Honeywell, and Litton each developed their own AINS design. The resulting systems—including ring-laser gyroscopes and stellar sensors—came to Draper for evaluation, laboratory testing, environmental testing, and rocket sled testing at Holloman Air Force Base, New Mexico. Following those challenging environmental tests, the Air Force elected to continue with the Mod AIRS as the most practical solution.

The Small ICBM completed two flight tests in 1989 and 1991. In response to the end of the Cold War, the Small ICBM program was terminated the following year.

In 1986, President Reagan authorized the development of a rail-road based Peacekeeper system called the Rail Garrison. Under this program, Draper developed a "Fifth Wheel" navigation system that, coupled with a hidden railroad track survey system to track the train's position, was successfully tested at the Transportation Test Center (TTC) in Colorado. The equipment was carried in a caboose provided by Draper and towed by an engine provided by TTC and later the Santa Fe Railroad.

Following the end of the Cold War, the Rail Garrison Program was terminated. In 1995, the Ballistic Missile Office closed, as did Norton Air Force Base. Responsibility for Peacekeeper transitioned to OO-ALC/ICBM SPO at Hill Air Force Base in Utah, which Draper supported until the Peacekeeper missiles were retired in 2005 under the Strategic Arms Limitation Treaty (SALT). At the closing ceremony that marked the removal of the last Peacekeeper missile from alert status, the Air Force credited the Peacekeeper with helping end the Cold War.

At a ceremony thanking employees for maintaining the missile since it became operational in 1988, Colonel Michael J. Carey, commander of the 90th Space Wing, said, "This is the world's most powerful weapon that was never fired, yet won a war."

Testing of the Peacekeeper Rail Garrison prototype land navigation system.

MINUTEMAN III

Since the retirement of Peacekeeper, the Minuteman III ICBM has been the only Air Force ballistic missile system deployed and on continuous alert. Minuteman III is the most responsive leg of the nuclear triad—with time to deployment of less than one minute. The current force of missiles has been in continuous service for more than 50 years, relying on a "remove and replace" approach to achieve an alert rate of nearly 100 percent. Draper continues our uninterrupted legacy of support for the program and will sustain the 16 PIGA until at least 2030, when the Air Force expects to replace Minuteman III with its successor, the Sentinel.

Draper has led or supported several research studies to inform the next-generation ICBM system design, developing new inertial instrument prototypes, test stations, and advanced aiding concepts. For example, under an internally funded effort in 2010, we developed a new Universal Test Station (UTS) that uses flexible, software-driven architecture to support a variety of strategic grade instruments. In 2014, the Air Force began sponsoring efforts to configure the UTS to replace aging legacy test equipment for the 16 PIGA sensor.

The UTS developed by Draper provides a modular approach for testing both existing and new inertial instruments.

The UTS dividing head used for mounting the sensor for testing

Air Force Global Strike Command unarmed Minuteman III ICBM launches at Vandenberg Space Force Base, Calif.

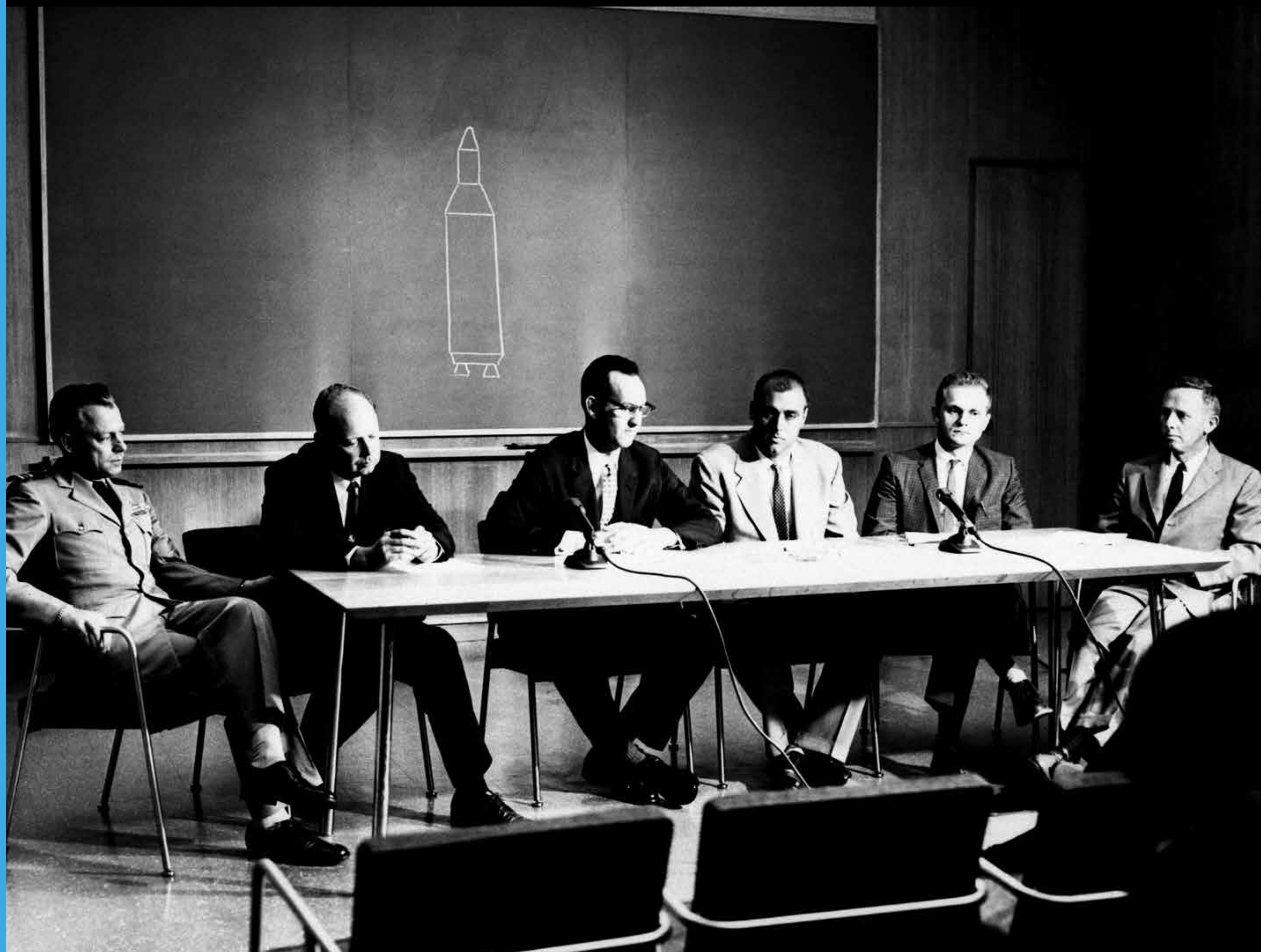
THE LGM-35A SENTINEL AND BEYOND

In 2014, the Air Force commissioned an analysis that identified a need to replace Minuteman III with a new missile system. Originally known as the Ground Based Strategic Deterrent and later dubbed the Sentinel, this program is designed to meet current and expected future threats by upgrading to modern approaches and technology. For example, the system employs a modular weapon system concept to reduce the life cycle cost.

Led by Northrup Grumman®, development of the LGM-35A Sentinel system began in September 2020, with an expected deployment date of 2029. As a key member of the Sentinel team, Draper is supporting the design, development, testing, and assessment efforts in key areas of the Sentinel weapon system—including the inertial measurement unit, strategic grade sensors, and radiation-hardened electronics. We are also providing flight-like environments for test article assessment. This test capability spans linear acceleration (centrifuge), shock, vibration, temperature/humidity, pressure/vacuum, angular rates, magnetic field, and radiation exposures.

As Air Force leadership seeks to leverage commercial technologies for strategic defense, Draper stands ready to apply our deep experience in GNC, modern digital engineering processes, and model-based systems engineering—reducing risk across the program and delivering cost-effective solutions in support of the nation's strategic defense needs.

(CHAPTER 4)



In July 1960, a press conference was held by the Laboratory following the success of the first test firing of the submarine-launched Polaris missile. Left to right, SP representative at MIT/IL, Cdr. Jack Padget, and members of the Lab's Polaris team: Forrey Houston, Ralph Ragan, Dick Haltmaier, Dave Hoag, and John Nugent.

The Navy's Guiding Star

THE UNDERWATER CHALLENGE FOR BALLISTIC MISSILE GUIDANCE

Since the advent of our nation's nuclear defense capabilities, the Department of Defense has been committed to safe, secure, and credible nuclear deterrence as a primary national security strategy. With almost unlimited cruising range, the Navy's nuclear submarines, carrying 16 or more nuclear-tipped ballistic missiles, are capable of extended submerged operation in international waters, allowing them to remain hidden from potential enemies by an oceanic curtain.

For more than 60 years Draper has played a critical part in ensuring that the Fleet Ballistic Missiles (FBMs) deployed by the Navy's submarines are capable of reaching their intended targets accurately. Every FBM deployed by the Navy—from Polaris A1 to Trident II—has been equipped with an inertial guidance system designed by Draper engineers. Our guidance systems ensure that the missiles remain on course while maintaining stability in pitch, yaw, and roll. Over the years, our guidance systems have improved weapon system accuracy by a factor of greater than 20 from Polaris to Trident II D5.

POLARIS

In early 1955, the Technological Capabilities Panel of President Eisenhower's Science Advisory Committee, chaired by MIT President James R. Killian, issued a report on defending the United States against the threat of surprise attack. One of the major recommendations of the Killian report was that priority should be given to the development of a sea-based strategic ballistic missile.

On November 17, 1955, the Secretary of the Navy created the Special Projects Office (SPO) under the direction of Rear Admiral William F. Raborn to handle the special problems associated with developing a ship-launched Intermediate Range Ballistic Missile (IRBM). Admiral Raborn flew up to Cambridge, Massachusetts, 11 months later with several members of his staff to solicit Draper's support for developing the guidance system for what would become the first ballistic missile launched from a submerged submarine. Nothing like this had been attempted before, and Draper was uniquely positioned to solve the complex guidance problems associated with such a challenge.

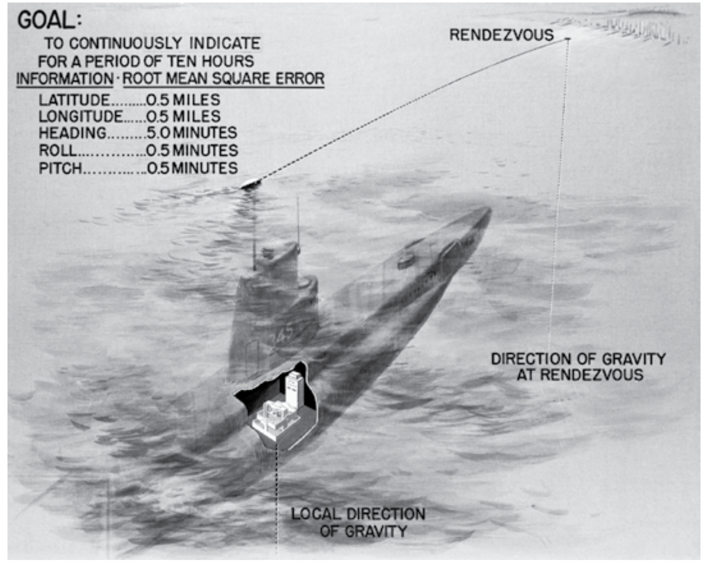
Launching a ballistic missile from a moving platform at sea added additional complexity to the already difficult challenge of designing a fire control and submarine navigation system to initiate the missile's inertial guidance system, given the weight and size limitations of the missile and its warhead. Unlike land-based missiles such as Atlas and Thor, the launching coordinates for Polaris would be changing constantly as the submarine cruised within its designated patrol area. The submarine's velocity and attitude would have to be determined precisely before firing—a function provided by the ship's own inertial navigation system.

To achieve accurate delivery of the warhead, the missile's guidance system would have to be updated continually without the external benchmarks available to land-based missiles. The limited space within the submarine precluded the installation of the large computers then required to compute missile trajectories using traditional methods. Instead, Draper had to devise a means of programming the guidance system based on position data obtained directly from the submarine's navigation system.

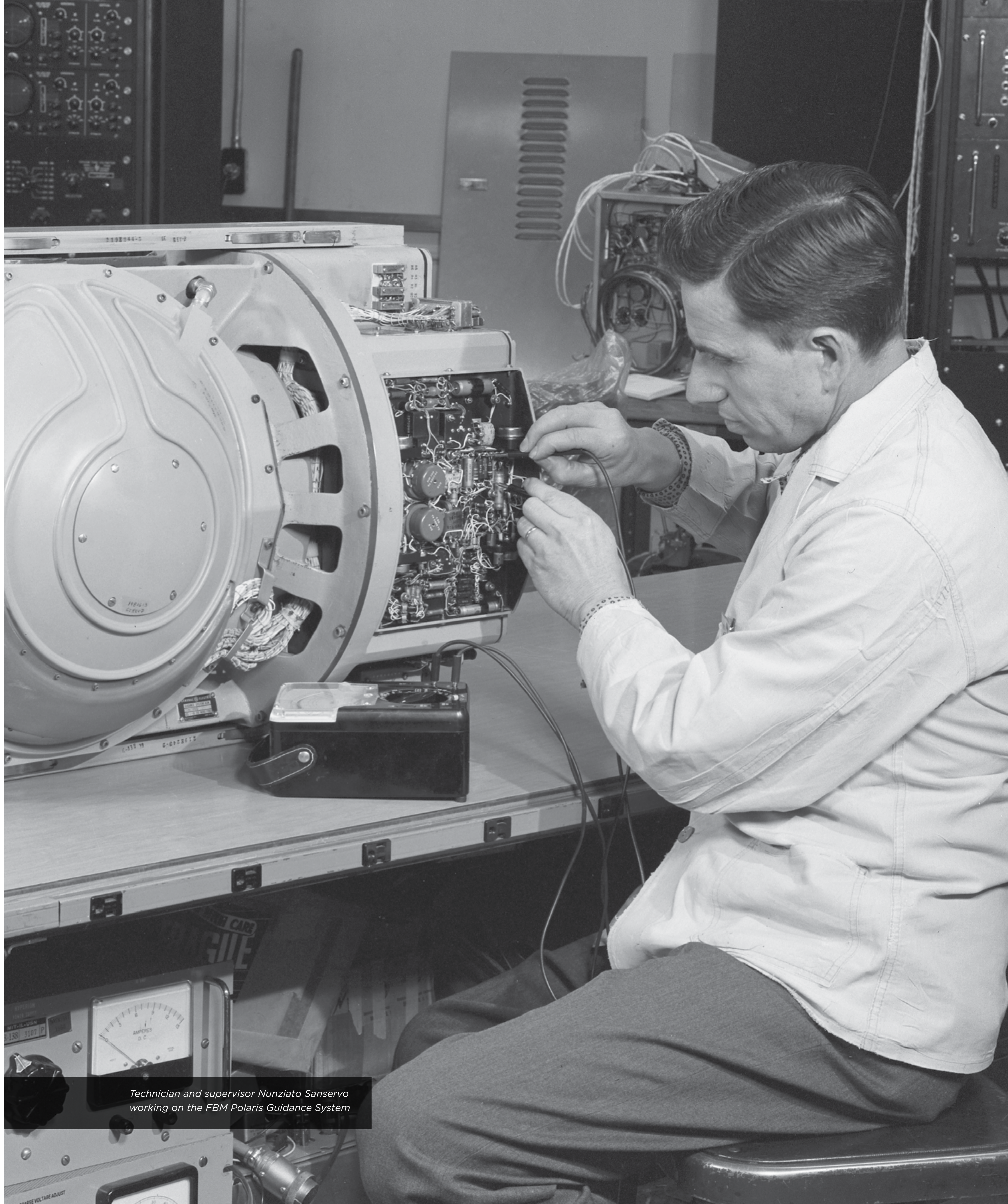
Raborn's staff believed that Draper Laboratory was the most qualified organization to solve the Polaris guidance problems. Under Doc's direction, we had successfully developed the Submarine Inertial Navigation System (SINS), which would be used to determine the launching position, and was well along in developing the Air Force's Thor inertial guidance system, which was similar in size and range to Polaris.

Although a team from the Redstone Arsenal in Huntsville, Alabama, was working on the guidance for an IRBM similar to Polaris, the technical director of SPO, Captain (later Vice Admiral) Levering Smith, felt that the Navy could work more closely with Draper's team and that Doc's fluid-floated gyro approach would be easier to adapt to the solid rocket motor accelerations. But the decision to go with the Draper Laboratory, as Levering Smith later recalled, "was driven more by Q-Guidance than anything else."

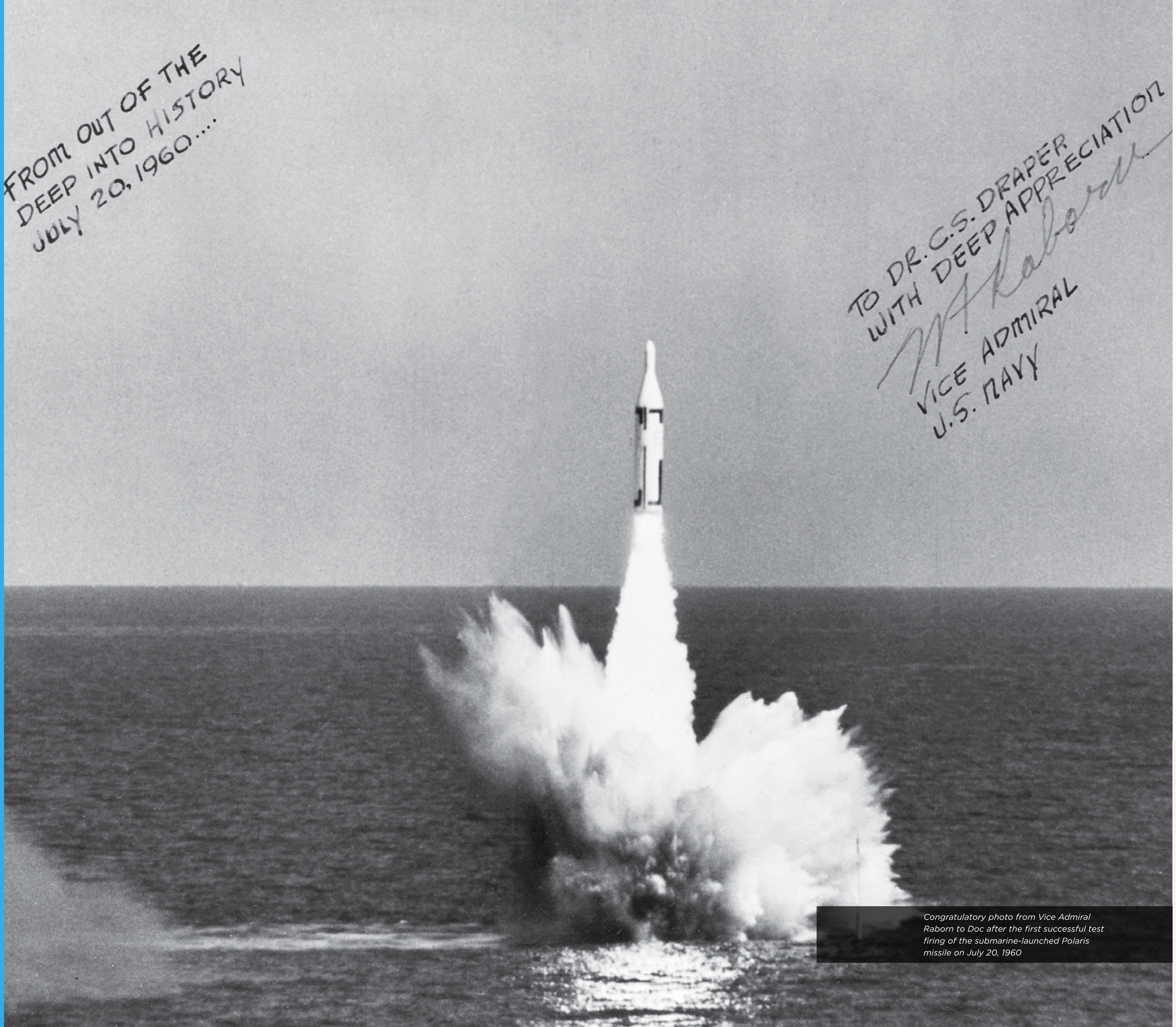
Q-Guidance was a new mathematical formulation developed by Hal Laning and Dick Battin that was particularly well suited to Polaris because it shifted much of the computation not only outside the missile, but also outside the submarine. Crucial data, such as the components of the Q-matrix, could be calculated onshore. Even though launch conditions could not be known in advance, as for land-based missiles, the Q-matrix left only fairly simple tasks for the submarine's fire control system and the missile's onboard computer.



Draper engineers delivered an experimental SINS— intended for submarines that would carry Polaris missiles—to the Bureau of Ships.



Technician and supervisor Nunziato Sanservo working on the FBM Polaris Guidance System



Congratulatory photo from Vice Admiral Raborn to Doc after the first successful test firing of the submarine-launched Polaris missile on July 20, 1960

Draper received a Navy contract to design and develop the guidance system that was to be built by a major industrial firm. Because we had no production capability, the General Electric Company was chosen to build the system and provide industrial support. The same design agent process was followed for the development of inertial guidance systems in all future submarine-launched ballistic missile programs—establishing the beginning of a close relationship between the Navy and Draper that continues to this day.

Working on a very tight schedule, which became even tighter in late 1957 following the October launch of Sputnik, Draper designed and developed the Polaris MK1 guidance system. The same guidance system was deployed in the improved Polaris A2 missile, which had a range of 1,500 nmi.

Thanks to Q-Guidance, improved gyros, printed circuit boards, and a digital computer—the first to be used aboard a ballistic missile—Draper made significant strides in reducing the size and weight of the MK1, which weighed only 225 lbs. This was about one-third the weight of Thor's 650-lb guidance package and less than the Jupiter C guidance package developed by the Army team at Huntsville. Although the constraints on weight and volume combined with a tight delivery schedule created a significant challenge, we successfully delivered the MK1 guidance system in time to meet the early deployment date set by the Navy for the Polaris A1.

As work on the Polaris A1 and A2 missiles was proceeding on schedule, SPO began to consider another generation of Polaris missile, the A3, which was designed to carry three multiple reentry vehicles (MRVs).

In addition to the greater payload, the A3 would have a range of 2,500 nmi. To meet these requirements, the guidance system would have to be further reduced in size and weight. Draper's team already had begun work on an improved computer that would be smaller, more reliable, and easier to maintain. In the meantime, Doc's unceasing drive to improve the single-DOF gyro led to the development of smaller instruments that were more sensitive. As a result of all these developments, the MK2 guidance system was half as large as and weighed 40% less than the MK1. Nevertheless, it was able to guide the A3 missile the additional distance with greater accuracy, giving the A3 a CEP of about 0.5 nmi compared with a CEP of 2 nmi for the two earlier versions of Polaris.

When Raborn and his team arrived at MIT on October 10, 1956, to persuade Doc to undertake the project, Doc began the conversation by sharing his concerns about how systems he had built for the military in the past had been poorly managed once they were turned over to industry for production. He was concerned about the high risk to a program as important as Polaris and did not want to take the job if he could not see the work completed through production.

Rear Admiral Robert Wertheim, then a young lieutenant who had been brought along to take notes, recalled:

> *Admiral Raborn figuratively swore on a stack of bibles that Draper would have full responsibility for the guidance system that they wanted him to build for the Navy. The transition from R&D to industrial practice would be under his oversight and control.*

And Raborn followed through on his promise.

POSEIDON

The development of the Polaris A3 missile was seen by Navy leadership as a logical extension of the FBM role established by the A1 and A2 missiles—that is, deterrence by the threat of devastating counter-city retaliation.

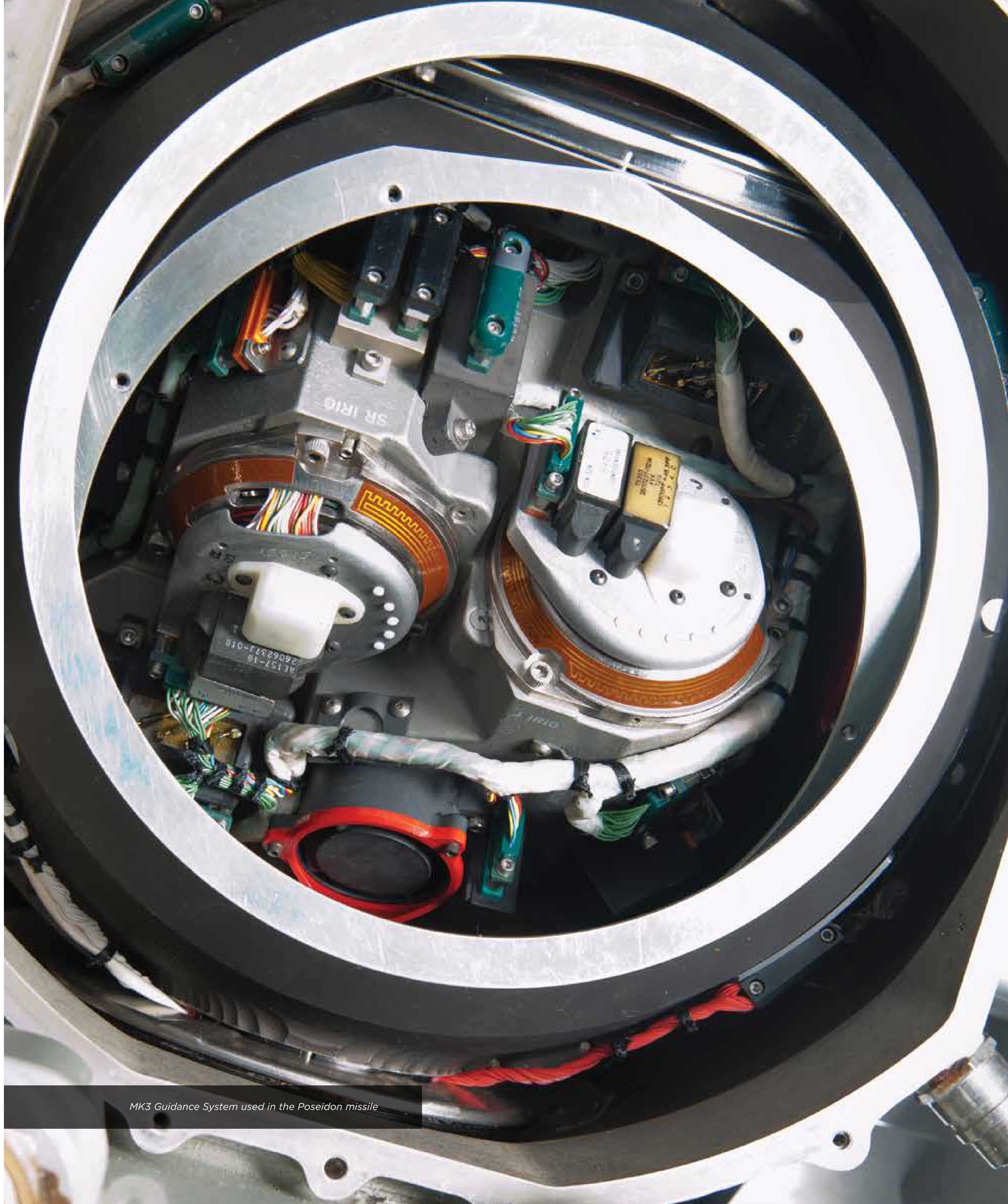
Although some favored more emphasis on enhancing the counter-force capabilities of the A3, the missile's payload was not optimized for this purpose. This was not to be the case for Polaris's successor, the Poseidon C3, which began development in 1965. The new missile would have more than twice the payload of Polaris, be more accurate and be capable of delivering up to 14 low-yield, multiple independently targeted reentry vehicle (MIRV) warheads over the same range as Polaris A3. Each MIRV warhead could be targeted to strike separate targets simultaneously.

Poseidon's mission constraints were so different from Polaris that a completely new guidance system, the MK3, had to be developed. This meant more work for Draper, whose size, both facilities and staff, became a matter of concern to the MIT administration. MIT Vice President James McCormack investigated whether the laboratory should be allowed to take on the work, eventually concluding that our services were critical for national defense. This ensured the continuation of Draper Laboratory's role as the Navy's chief design agent for inertial guidance.

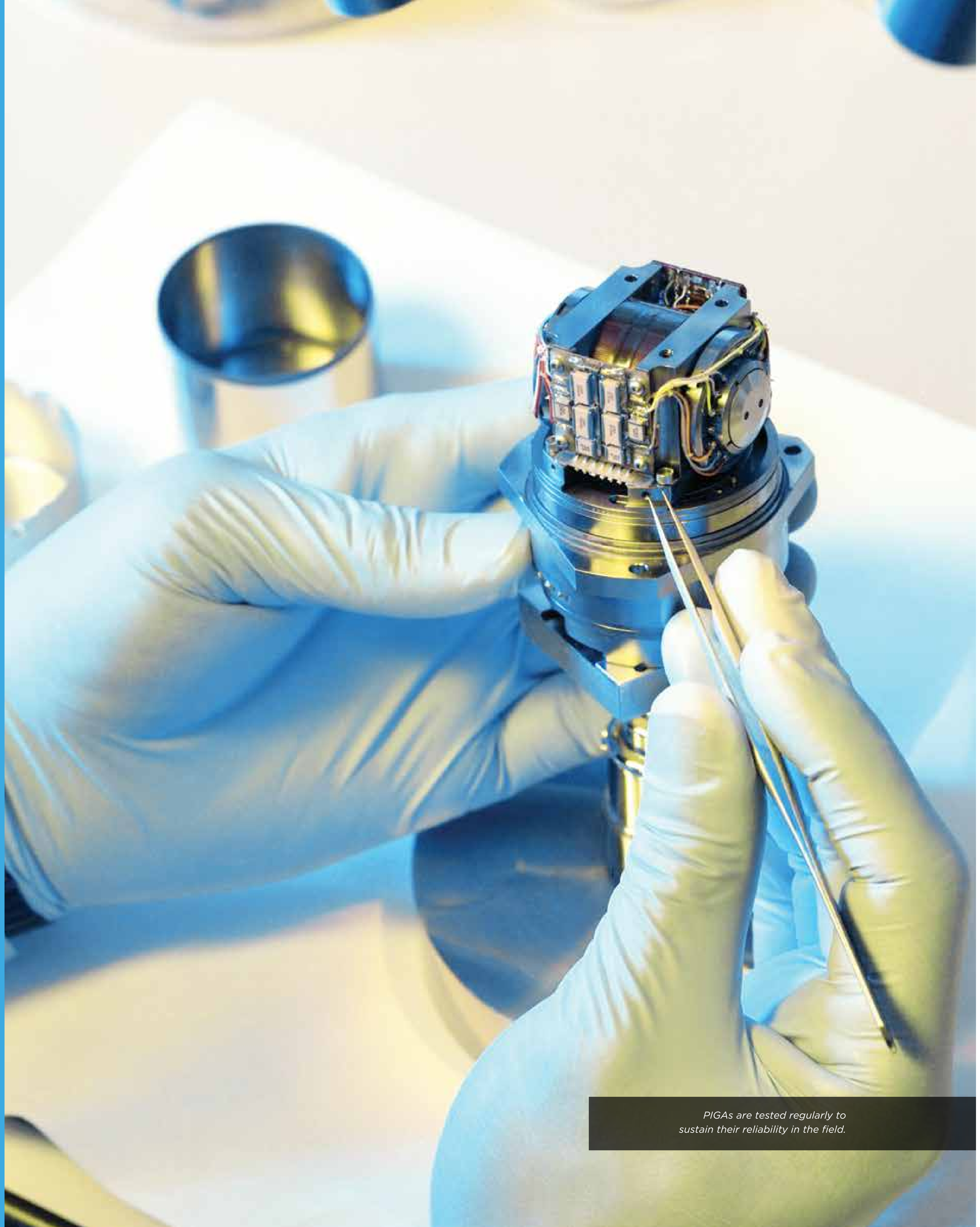
To achieve the accuracy required, Draper engineers designed improved gyros and accelerometers, abandoned Q-Guidance in favor of explicit guidance and added a more powerful computer based on the one we had developed for the Apollo Program.

While the MK3 guidance system was being designed, the Secretary of Defense proposed the development of an improved guidance system for Poseidon that would provide a greater degree of accuracy, enhancing its effectiveness against hard targets. To achieve this goal, the Draper team fitted a stellar sensor to the inertial measurement unit (IMU) case for taking a star sighting following the boost phase. This information was used to correct any errors in the initial launch position. It was developed as the MK4 guidance system, but never entered production due to political concerns at the time regarding its first-strike capability.

Exploded view of the MK3 Poseidon gimbal assembly MK3 Guidance System used in the Poseidon missile



MK3 Guidance System used in the Poseidon missile



PIGAs are tested regularly to sustain their reliability in the field.

TRIDENT I

The development of the Navy's fifth-generation FBM, the Trident I C4 missile, began in 1971 in response to growing concerns about the Soviet Union's antisubmarine capabilities. The longer range of the Trident C4, which was twice that of the Poseidon, would provide more sea room into which the nuclear submarines could be deployed, alleviating some of these concerns. To ensure that Trident I C4's accuracy at 4,000 nmi was as good as Poseidon's at 2,000 nmi required adding a stellar sighting system similar to the one used in the MK4.

Once again, the Draper Laboratory was selected by the Navy's SPO to have overall design and development responsibility for the guidance system. Draper also had an expanded role in several support areas—including system testing and evaluation, design and documentation, materials evaluation and approval, reliability assessment, test equipment development, and flight test program support.

The MK5 guidance system developed for Trident I was the first inertial guidance system designed by Draper that was not based on the single-DOF floated gyro. Instead, the design team determined that the same degree of accuracy could be obtained using two dry-tuned, two-DOF gyros. These were lighter, smaller, and less expensive than the three single-DOF gyros then available. Building on its experience with the MK4 inertial guidance system, the design team added a star sensor consisting of a vidicon tube with Maksutov-Magnin optics mounted on the stable member with the gyroscopes and accelerometers. Draper also designed the computer and control electronics housed in a separate electronics assembly.

TRIDENT II

The sixth submarine-launched ballistic missile developed by the Navy was the Trident II D5. Development of the missile's guidance system began in 1981 when Draper received a three-year contract for advanced development of the MK6 guidance system. The push for a hard target—missile silos and command and control facilities—was the central factor affecting the MK6 design, which relied heavily on data obtained from the Improved Accuracy Program conducted by Draper and other SPO contractors in the mid-1970s.

Preliminary design studies for the Trident II guidance package showed that the computing power available for the MK6 combined with a stellar sighting allowed the system to compensate for gyro drift, but that acceleration sensing error was still an important source of inaccuracy. Although other technologies for sensing acceleration were emerging, Draper's Pendulous Integrating Gyroscopic Accelerometer (PIGA), which had been continually improved over the years, was still considered to be the most accurate means of determining acceleration and was included in the design. For the MK6 Guidance System, Draper developed an improved and smaller PIGA, the 10 PIGA. The 10 PIGA—and its later derivative, the Alt PIGA—remain the most accurate strategic-grade accelerometers ever produced.

Like its predecessor, the MK6 consisted of an inertial measurement unit (IMU) package and an electronics assembly. The IMU featured improved inertial instruments and an advanced stable member for a more stable thermal and mechanical environment. A new star tracker based on a silicon solid-state charge-coupled device (CCD) replaced the vidicon, providing a self-contained method of alignment lacked by the MK5. The electronics assembly contained six computers that handle gimbal control, safety and error monitoring, steering, and navigation data. An all-digital system, the MK6 was able to maximize signal-to-noise to improve the accuracy of instruments and servos by reducing systematic errors. A testament to the outstanding engineering capabilities of Draper, the MK6 MOD 0 Guidance System exceeded its original requirements, providing the US and our allies with a highly accurate and reliable strategic deterrent. From its first deployment in 1990, the MK6 MOD 0 Guidance System has been a stalwart component of the SLBM—a legacy that will continue through to its final expected deployment around 2025.

The opening of the Integrated Support Facility for Navy guidance system repair in Pittsfield, Mass., was marked by a ribbon-cutting ceremony. (First row, from left) CDR Johnny Wolfe, Rhonda Serre, Capt. Terry Benedict, Draper President & CEO Jim Shields, Pittsfield Mayor James Ruberto, Richard Johnston, Mike Tweed-Kent; (second row, from left) Ray Majewski, CDR Kaufman, Steve DiTullio, Draper Vice President John Stillwell, LTC Kelvin Wood; (third row, from left) Bob Krum, Bill Rhorer, Steve Sloboda and Don Benzing.

MK6 LIFE EXTENSION PROGRAM AND NEXT-GENERATION GUIDANCE SYSTEM

Following the deployment of the MK6, the 50-plus-year program that engineered six Navy strategic guidance systems transitioned from designing ever more capable systems to sustaining the guidance system and supporting the fleet. With no new missiles on the horizon, the Strategic Systems Program Office (SSP),* which had acted as prime contractor for each guidance system with Draper as its sole-source design agent, drastically reduced the workforce that had been responsible for producing the MK1 through MK6 guidance systems.

By the end of the decade, it was clear to SSP staff that they could no longer act as prime contractor for the guidance systems.

Although they believed that Draper was best suited to take over this role, SSP was concerned that the company was not organized to assume these additional responsibilities. Draper President Vince Vitto led discussions with Department of Defense (DOD) leadership to clarify that Draper was uniquely capable of overseeing this critical national program. To ensure success, Vitto recruited recently retired Navy Captain John Stillwell to lead the program, solidifying vital links between the Navy's operations and Draper's technology leadership. Draper was selected, and since 2001 we have been the Navy's prime contractor for the MK6 guidance program responsible for design, maintenance, repair, overhaul, and fleet support.

When the Navy announced plans to extend the life of its D5 missile through 2042, Draper was assigned the task of updating the missile's MK6 guidance system—which was based on 20-year-old technology—with what the Navy termed the "Next-Generation Guidance." To meet the demanding goals established for the Trident II D5 Life Extension (MK6LE) program, Draper was charged with replacing the guidance system's obsolete components at minimal cost while maintaining the demonstrated performance of the existing Trident II missile.

Our engineers achieved this goal by replacing the mechanical gyros with solid-state interferometric fiber-optic gyros (IFOGs), upgrading the PIGA by eliminating several failure and wear-out mechanisms; replacing the obsolete CCD stellar sensor with an improved model with greater resolution; and incorporating a modular, subsystem-dedicated, individual board-based electronics architecture that is easy to maintain and can be upgraded easily to meet future changes in technology and industrial practice.

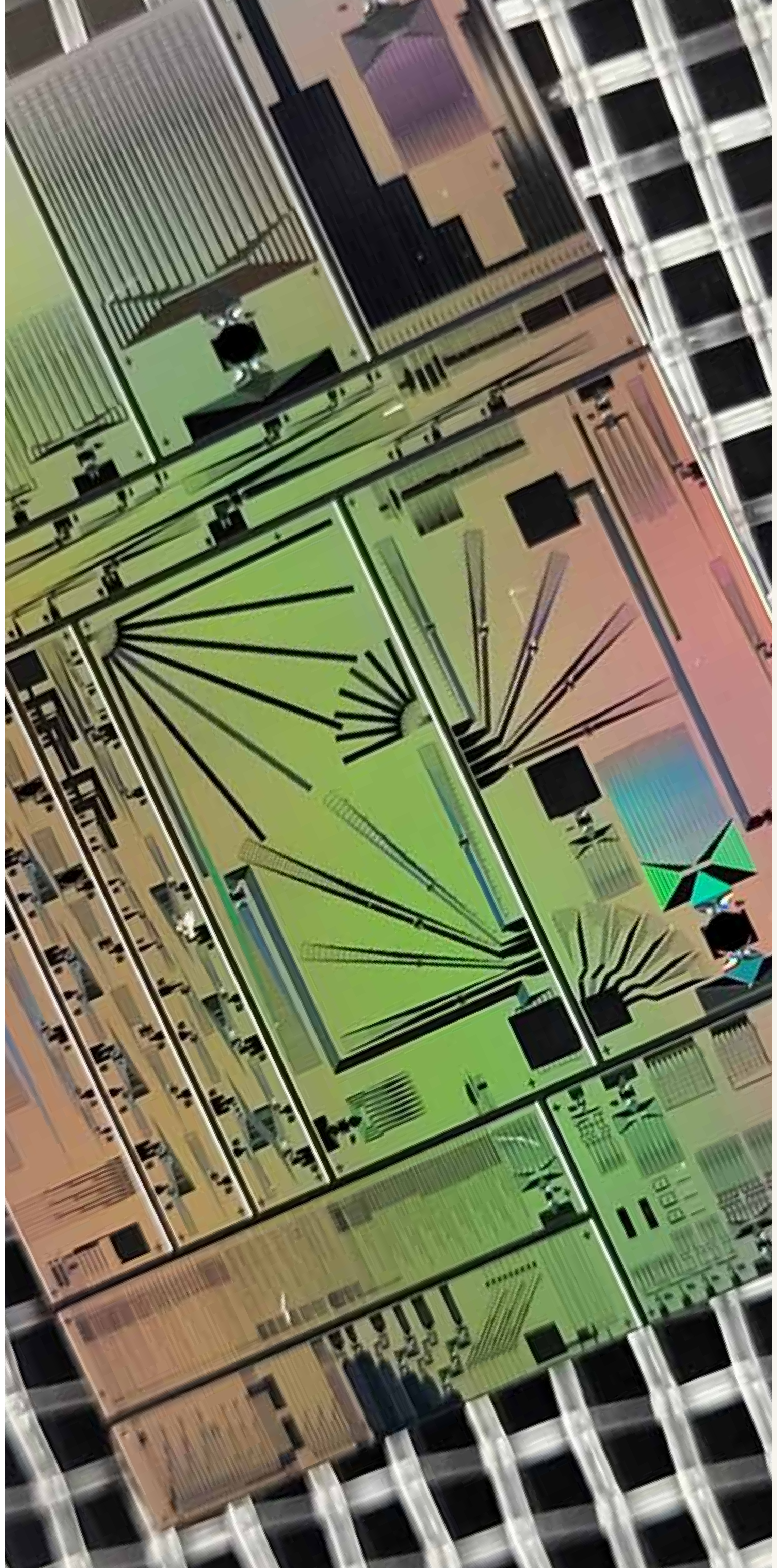
After successfully completing the first prototype in 2007, Draper was awarded a $318 million contract to produce the MK6 MOD 1 guidance system. In that same year, we also began delivering guidance hardware to the fleet from the new Integrated Support Facility (ISF) in Pittsfield, Massachusetts, which was established to reduce support costs by consolidating the guidance system depot-level repair in a single location.

The first flight test of the MK6 MOD 1 guidance system took place on February 22, 2012, when a Trident D5 carrying the new guidance package was launched from the USS Tennessee (SSBN 734) and successfully flown down range to its target. It had been 22 years since the Tennessee became the first Ohio-class SSBN to launch a Trident II D5 missile. The flight testing of the MK6 MOD 1 guidance system—which took place on time and on budget—was made possible through Draper's successful validation of the MK6 MOD 1 design with new modeling, simulation, and hardware-in-the-loop integration and test capability.

In November 2016, the MK6 MOD 1 Guidance System was initially introduced into the fleet, with full deployment slated for 2025. By 2023, the MK6 MOD 1 had successfully completed 29 out of 29 flight demonstrations, meeting all performance expectations and achieving Draper's long-established high bar for accuracy and reliability in our guidance systems. The flexible, modular design of the MK6 MOD 1 system also enables other mission-critical capabilities—including Multi-Star Enhanced Prelaunch (MEP), which enhances operational flexibility by loosening requirements for the submarine's initial position and velocity at launch while still maintaining overall accuracy.

As the prime contractor for the MOD 1 Guidance System, Draper has cradle-to-grave responsibility for the system. To ensure the system consistently delivers extremely high performance in the deployed fleet, we established an enhanced surveillance and sustainment program. Our engineers built in both predictive and prognostic capabilities, enabling prediction of failures before they occur and providing timely corrective actions—and thereby maximizing operational readiness for our nation's warfighters throughout the system's lifecycle.

* The Special Projects Office was officially redesignated the Strategic Systems Program Office on July 29, 1968.



ADAPTING COMMERCIAL TECHNOLOGIES FOR STRATEGIC-GRADE PERFORMANCE

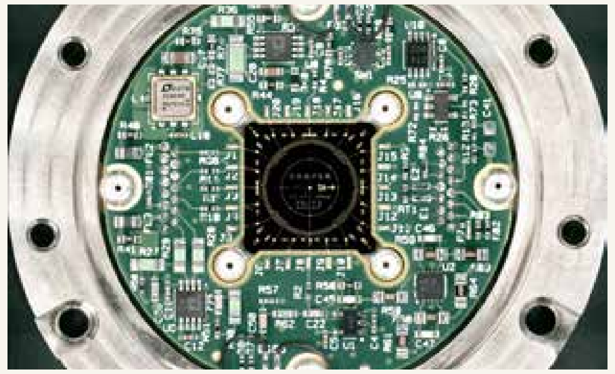
Draper's mandate for the MARK 6 MOD 1 upgrade was to contain costs while maintaining the demonstrated performance of the existing Trident II missile guidance system. To meet those goals, our engineers adapted commercial hardware to ensure its GNC system could withstand the mechanical and thermal shock of vibration through boost stages, as well as potentially numerous bursts of high-energy ionizing radiation.

Applying unmatched expertise in radiation-hardened (rad-hard) design, Draper modified commercial hardware—including gyroscopes, computers, accelerometers, application-specific integrated circuits (ASICs) and their associated memories and other components. We designed all aspects of the guidance architecture to detect, absorb, and recover from radiation while maintaining a high degree of precision.

For example, building on the random access memory (RAM) used in everyday computers, we worked with industry partners to design magnetoresistive random access memory (MRAM). By storing data using magnets instead of electrical charges, the MRAM solution maintains stability even when subject to extreme radiation bursts.

Similarly, our team selected an advanced commercial gyroscope technology for its performance, cost, and stability and adapted it to meet the strategic-grade mission. The interferometric fiber-optic gyro (IFOG) senses change in orientation by measuring the rotation rate of light traveling in fiber optic coils. To design an IFOG that would meet strategic performance demands, Draper engineers scaled optical fibers to diameters thinner than a human hair and coiled them for lengths of up to several kilometers. The resulting technology represents the first practical application of what has previously been only theoretical approaches. Ultimately, two versions of the IFOG were chosen for the weapons' subsystems: one for the MK6 MOD 1 missile guidance system and another for the Trident submarine navigation system. Both require little maintenance and are less vulnerable to the effects of intense heat, shock, vibration, and radiation of missile launch and flight than the earlier mechanical gyroscope.

The need for strategic-grade technologies spans national security and space missions. Draper's rad-hard innovations and the expertise developed through the MK6 MOD 1 program will continue to serve our nation by enabling reliable missile defense and scientific exploration of the most extreme environments.



Draper continues to design innovative GNC solutions to support the Strategic Deterrent mission.

LIFE EXTENSION 2 AND BEYOND

For the first time in our history, the nation is on a trajectory to face two nuclear-capable, strategic peer adversaries at the same time, who must be deterred differently. We can no longer assume the risk of strategic deterrence failure in conflict will always remain low.

- Admiral Charles Richard, Commander, STRATCOM, speaking to the Senate Committee on Armed Services in April 2021

In 2010, Congress authorized the Columbia-class submarine program and extended the Navy's sea-based strategic deterrence mission into the 2080s. The plan called for deploying Columbia with the existing Trident II D5LE missile; however, in 2019 the Strategic Systems Program began a second Trident II life extension program (D5LE2) to be deployed by 2039. The goals of this program include ensuring credible deterrence under rapidly evolving threats, replacing aging and obsolete technologies, and ensuring sufficient missile inventory. Unlike D5LE, which modernized missile and guidance electronics and inertial guidance sensors, D5LE2 will modernize the entire Trident weapon system to ensure its effectiveness throughout the life of the Columbia submarine.

Under D5LE2, Draper's legacy as the Navy's prime contractor for GNC of America's Sea-Based Strategic Deterrent (SBSD) continues. In 2021, we were tasked with exploring and evaluating maturing concepts and technologies to enable follow on, full-scale development of the D5LE2 GNC system. Our engineers are seizing the opportunity to update the strategic weapon system, including a design refresh of the avionics and guidance.

The D5LE2 program faces significant challenges, including emergent and constantly evolving in-flight and cyber threats. As Draper tackles these challenges, we will push the boundaries of strategic GNC technologies to provide our nation with a defense system and deterrent that maintains its long history of demonstrated performance, achieves new levels of resilience, and can adapt at the speed of relevance.

As our nation anticipates the future, the importance of the Strategic Deterrent mission has never been greater. China's rapidly expanding military capabilities and its coercive activity toward Taiwan threaten to destabilize the Indo-Pacific region, and Russia's unprovoked invasion of Ukraine in 2022 escalated the nuclear risk posture around the globe.

As the Department of Defense works to ensure our nuclear forces maintain a credible threat to these and other adversaries, Draper stands ready as a key partner—designing and delivering innovative GNC solutions that meet increasingly rigorous demands for accuracy and reliability.

The MK6LE team achieved a successful Preliminary Design Review in September 2005.

(CHAPTER 5)

Milt Trageser (center) led a project to design a recoverable interplanetary Mars space probe. The engineering team included Hal Laning (left) and Dick Battin (right), whose original formulations were used in the project's guidance system.

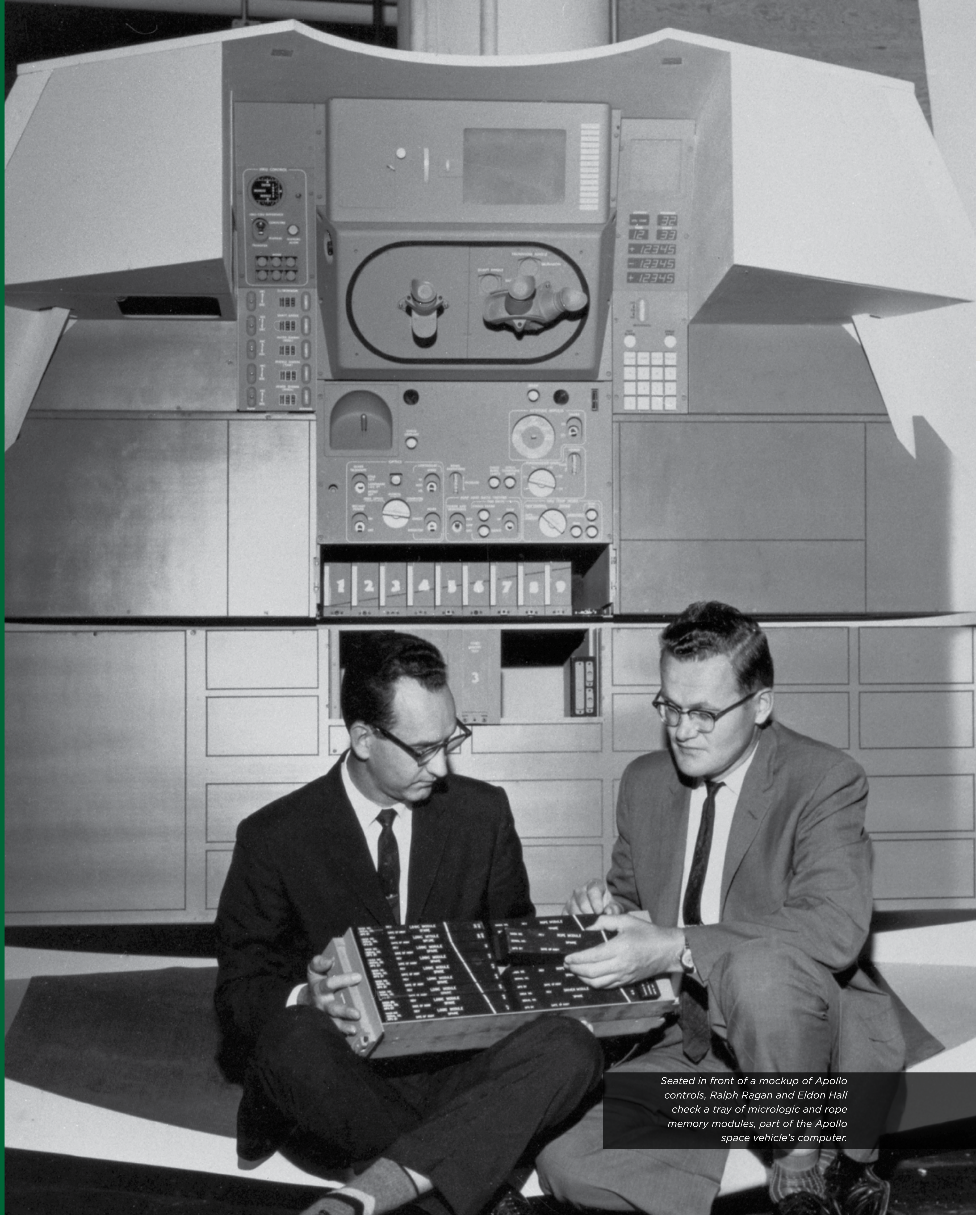
From Apollo to Artemis and Beyond

SUPPORTING HUMAN SPACE FLIGHT SINCE THE 1950s

While Draper was hard at work on the Navy's new FBM program in the late 1950s, the Air Force Ballistic Missile Division asked the laboratory to work on a preliminary design study for a Mars space probe. We received a contract in 1957 to study the technical feasibility of conducting an uncrewed photographic reconnaissance mission to Mars, and a small team of engineers led by Milt Trageser immediately set out to design an autonomous spacecraft that could take close-up, high-resolution photographs of the planet.

The guidance program developed for the project used original formulations, designed by Hal Laning and Dick Battin, to operate a small rocket motor at appropriate times and put the spacecraft on a corrected trajectory using Martian gravity to send it back to Earth. To control the autonomous operation of the spacecraft, Ray Alonso designed a small general-purpose digital computer, configured to operate at very low power.

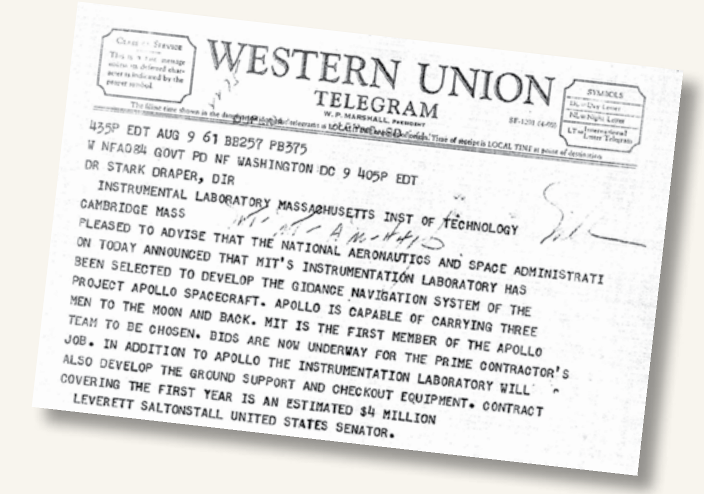
After the Air Force contract ended, a small follow-on project from NASA allowed the Mars group to continue its work. Laning's interest in computers—he wrote the first algebraic compiler, dubbed George—led him to join forces with Alonso to further refine the configuration of the digital computer. Eventually, the technical offspring of that computer would take humans to the Moon.



Seated in front of a mockup of Apollo controls, Ralph Ragan and Eldon Hall check a tray of micrologic and rope memory modules, part of the Apollo space vehicle's computer.

I was invited to Washington for a conference with Mr. James E. Webb, then the Administrator of NASA. After some preliminary explanations of the mission plan being considered for Apollo, Mr. Webb, Dr. Hugh Dryden (Technical Director), and Dr. Robert C. Seamans (Deputy Administrator) asked the Lab's Program Manager Milton Trageser and me if guidance for the mission would be feasible during the 1960s decade. We said, 'Yes.' They asked when the equipment would be ready. We said, 'Before you need it.' Finally, they asked, 'How do we know you are telling the truth?' I said, 'I'll go along and run it.'

- Doc Draper



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DR STARK DRAPER, DIR
INSTRUMENTAL LABORATORY MASSACHUSETTS INST OF TECHNOLOGY
CAMBRIDGE MASS
PLEASED TO ADVISE THAT THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATI
ON TODAY ANNOUNCED THAT MIT'S INSTRUMENTATION LABORATORY HAS
BEEN SELECTED TO DEVELOP THE GIDANCE NAVIGATION SYSTEM OF THE
PROJECT APOLLO SPACECRAFT. APOLLO IS CAPABLE OF CARRYING THREE
MEN TO THE MOON AND BACK. MIT IS THE FIRST MEMBER OF THE APOLLO
TEAM TO BE CHOSEN. BIDS ARE NOW UNDERWAY FOR THE PRIME CONTRACTOR'S
JOB. IN ADDITION TO APOLLO THE INSTRUMENTATION LABORATORY WILL
ALSO DEVELOP THE GROUND SUPPORT AND CHECKOUT EQUIPMENT. CONTRACT
COVERING THE FIRST YEAR IS AN ESTIMATED $4 MILLION
LEVERETT SALTONSTALL UNITED STATES SENATOR.

APOLLO

Draper's involvement with the Apollo Program started in November 1960, when Doc Draper met with the chairman of the NASA Steering Committee on Manned Space Flight to discuss the guidance, navigation, and control (GNC) system that would be needed to reach the Moon. This led to a meeting at Goddard Space Flight Center, where Draper's technical personnel helped formulate a six-month contract for a preliminary design study. Awarded in February 1961, this contract laid the groundwork for a decade of work for NASA on Apollo. That August, Draper received a development contract for the Apollo GNC system—the first major contract issued by NASA for the Apollo Program.

Under the technical direction of Dave Hoag, the system supported several functions—including onboard measurement of rotational and translational motions, processing of those measurements for display to the crew and ground control, acceptance from the crew or ground control of desired maneuver instructions, and execution of those maneuvers by firing the rocket propulsion systems.

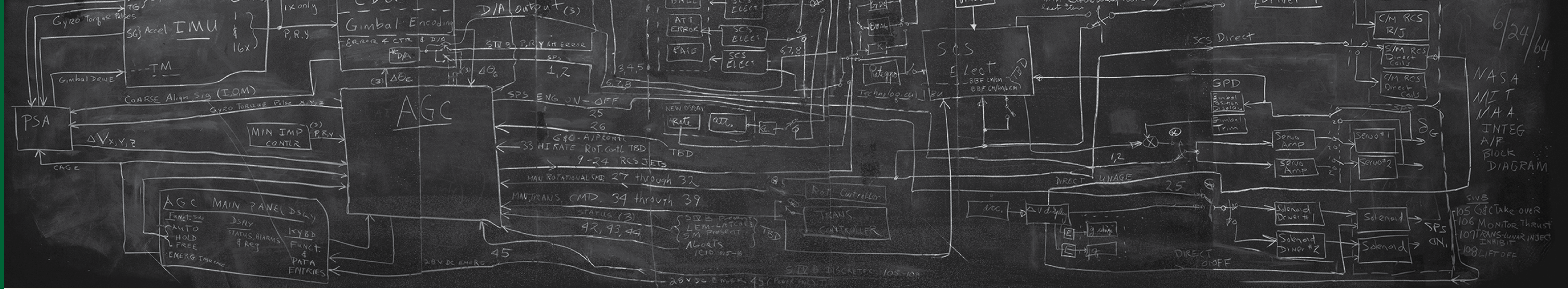
The Apollo Guidance Computer was the first real-time embedded computing system. For its pioneering contributions and historic development of the computer, Draper received an IEEE Milestone Award in 2011.

In those years, Draper was fundamentally a guidance and control organization. The word "programming" appeared only twice in the original work statement, but the contract explicitly required that the onboard guidance computer be "programmed to control the other guidance subsystems and to implement the various guidance schemes." In hindsight, however, it's clear that Draper's digital computer and its programming became the most important technology for achieving NASA's goal of reaching the Moon.

Software engineering was an unknown discipline when software development for the Apollo program got underway. As one of the original members of the computer team, Hugh Blair-Smith, recalled, "Nobody, not even NASA, knew how difficult it would be to develop such a large software project." Nevertheless, a few of Draper's engineers got started programming. Dick Battin, according to historian David Mindell, "was in charge, with a laid-back management style typical of dedicated academics." As experts and pioneers in their field, the team knew that nobody had accomplished what they were about to attempt, yet they never doubted that they would succeed.

Indeed, they did: No Apollo mission ever experienced a software failure during flight, a technical triumph that could only be credited to Draper engineers' dedication, motivation, and confidence.

Eldon Hall, who designed the Polaris missile computer, undertook the design of the hardware. He was assisted by Ray Alonso, Al Hopkins, and Hugh Blair-Smith. When they started the design program, the typical mainframe occupied an entire room and weighed about five tons. The computer they created weighed just 70 lb, consumed only 55 W of power, occupied just under 1 ft^3, and pioneered the first use of integrated circuits. The Apollo Command and Lunar Modules had their own computers, which were programmed individually for each module's mission.



The Apollo Block II Command Module GNC diagram at the Johnson Space Center. The illustration shows how the engineers integrated every key element into the design.

Doc Draper presents the Apollo Exceptional Service award to Don Eyles for his contributions to Apollo 14.

"HOUSTON, WE HAVE A PROBLEM…"

Under the Apollo Program, most flights unfolded as planned, thanks in part to software to detect system errors and recover from them in real time developed by Margaret Hamilton and the team of software engineers she led. But some missions experienced surprises and emergencies that compromised objectives and even endangered the crew. Draper engineers were often called in to help resolve these problems. Among the notable:

- Completion of the landing program after an overload of the Apollo 11 Lunar Module computer triggered crew alarms during the first lunar landing.
- The realignment of the Apollo 12 guidance system in Earth orbit after disturbance caused by two lightning strikes shortly after liftoff.
- The remarkable rescue of Apollo 13 using a little-tested program in the LM guidance computer to push the disabled Command/Service Module onto a safe return trajectory to Earth.
- The emergency transmission to the Apollo 14 Lunar Lander crew of a manual keystroke sequence developed hastily in Cambridge so that the computer would ignore erratic commands from a faulty switch that would otherwise have aborted the landing.

Draper was also responsible for providing the inertial guidance systems for both the Command Module and Lunar Module (LM). The inertial measurement units (IMUs) we developed borrowed heavily from our technical experience with Polaris. John Miller headed the engineering team for the design of the inertial system, which incorporated stellar alignment. Precision readouts for each gimbal angle were fed to the computer, where they were compared to angles of star sightings taken by the astronauts through a sophisticated optical system designed by Draper engineers.

Our team also developed the flight control mechanism for the LM. Although it was officially described as the Primary Guidance, Navigation, and Control System, it was more commonly known by the acronym PGNCS (pronounced "pings"). Neil Armstrong used it to pilot the LM to the Moon's surface on July 20, 1969. The system, which relied on the complex algorithms developed by the Draper software team, ran on the LM's digital computer, making it the first Digital Fly-by-Wire (DFBW) system ever developed.

Apollo's GNC system performed nearly flawlessly during the eight orbital and nine crewed lunar missions conducted during the Apollo Program. Because of its success, Draper became NASA's "go-to" source for guidance and control for both crewed and uncrewed spacecraft. Since Apollo, we have participated in every human space flight program conducted by NASA and our engineers continue to provide guidance and control for the nation's space program.

DIGITAL FLY-BY-WIRE

After completing the historic mission to the moon, Neil Armstrong served as Deputy Associate Administrator for Aeronautics at NASA Headquarters. He was approached by two engineers from Dryden Flight Research Center seeking funds to investigate the advantages and performance of an all-electronic, analog aircraft flight control system. To their surprise, Armstrong objected:

> *'Why analog technology?' he asked. Rather than a system that sends impulses, he proposed a more advanced system, one based on digital fly-by-wire. [The engineers] knew of no flight-qualified digital computer. 'I just went to the moon and back on one,' said Armstrong. 'Have you looked at the Apollo system?' The visitors from the Flight Research Center admitted with embarrassment they had not even thought of it.*
>
> - Michael H. Gorn, Expanding the Envelope: Flight Research at NACA and NASA, 2001

As Dryden engineers undertook efforts to outfit an F-8 aircraft for their test bed, they knew the Apollo computers were the most reliable computers in existence. The Dryden team traveled to Cambridge and briefed Dr. George Cherry, head of Draper's Guidance and Control Division, who agreed to provide support. This resulted in the transfer of Draper's space technology to the world of aeronautics.

Designed and developed by Draper and NASA Dryden, the DFBW system replaced mechanical flight control, eliminating bulky hydraulics, cables, rods, and pulleys. This allowed for increased payloads, greater range of flight, and improved safety. The system was first flown in 1972 and was the forerunner of DFBW systems in wide use today. For this achievement, Draper Laboratory was inducted into the Space Technology Hall of Fame in 2010, and two staff members—Philip Felleman and Robert Bairnsfather—received honors.

Draper pioneered the DFBW system in collaboration with NASA.

The F-8 was the test bed for the highly reliable, fault-tolerant avionics systems concepts Draper developed with NASA Dryden.

THE LEGACY OF FAULT-TOLERANT COMPUTING

The highly reliable, fault-tolerant avionics system concepts that Draper developed under the F-8 DFBW program became the standard architecture for future aircraft and spacecraft.

In military airplanes, our DFBW system allowed the use of sophisticated stability augmentation systems that significantly improved aircraft maneuverability. The technology was immediately adopted in the F-16 and all subsequent fighter aircraft. DFBW enabled the first use of stealth technology in the F-117A and the B 2, neither of which could be flown without active flight control. Draper's innovation also found a home in commercial airliners and military submarines for its weight savings and reliability. First implemented commercially in the Airbus 320 and later in the Boeing 777, Draper later applied the technology on the ship control system we developed for the Seawolf class of nuclear-powered fast-attack submarines.

In space flight, various versions of Draper's technology have powered NASA's human spacecraft since the Shuttle, as well as launch rockets and uncrewed vehicles. In the late '90s, we developed and flight qualified fault-tolerant computers for NASA's X-38 spacecraft, an experimental return vehicle for the International Space Station crew. Although the program was canceled in 2002, Draper's fault-tolerant architecture served as the foundation for future work including the future Space Launch System.

For the Space Launch System, a program that began in 2011 and resulted in NASA's highest payload capacity rocket ever, Draper designed a flight computer with an innovative, software-based redundancy management system for fault detection, containment, and recovery. Draper also designed the computers that operate Northrup Grumman's Cygnus cargo spacecraft, which completed 18 successful resupply missions to the International Space Station between 2014 and 2022. In 2016, we designed, developed, and delivered the human-rated, fault-tolerant computers and GNC software for Sierra Space's Dream Chaser®, the world's only winged commercial spaceplane. The lifting body vehicle—similar to the Space Shuttle—is under contract with NASA for a minimum of seven missions to resupply the International Space Station. Dream Chaser can safely carry cargo—and eventually crew—to on-orbit destinations, returning to land on compatible commercial airport runways worldwide.

THE SPACE SHUTTLE

As Draper's work on Apollo was winding down, we were awarded a contract to support development of avionics and the ascent GNC system for the Space Shuttle, bringing a new series of challenges to our technical staff.

Because the Shuttle was to be the first spacecraft capable of returning from orbit and landing on a conventional runway, it required the most complex and sophisticated control system ever devised for space travel. It was a rocket booster, an orbiting platform, a reentry vehicle, and an aircraft. The GNC system specified by NASA would have to safely control the Shuttle as it maneuvered from the vacuum of space, through the heat of atmospheric reentry, to an unpowered landing on an ordinary runway. It was not feasible to use the Apollo hardware and its computer for the Shuttle, and the cost of designing a new, single computer that was as reliable was so high that NASA adopted an alternate strategy based on using multiple computers, all running the same program and continuously comparing their outputs.

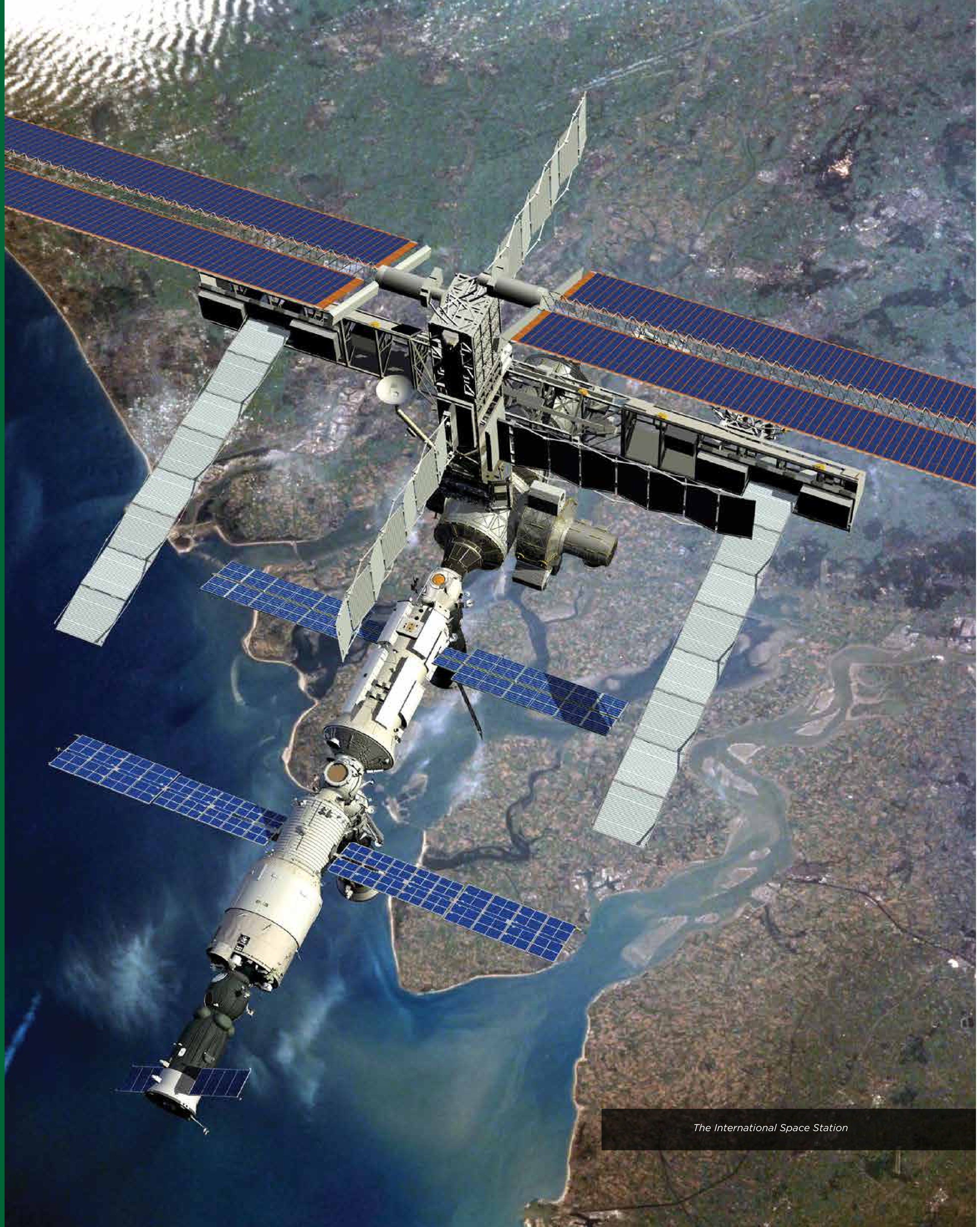
Draper provided substantial input to help develop the Shuttle's fault-tolerant avionics system, leveraging the work done with NASA's Dryden Flight Research Center on the F-8 DFBW program. The flight control system—dubbed the Primary Avionics Software Set (PASS)—used four independent AP-101 computers working in parallel. At each critical step, the computers "voted" to determine the appropriate step. There was also a Backup Flight System, programmed by Rockwell, that the crew could engage if the primary system failed.

Working closely with NASA's Johnson Space Center, Draper led the development of the GNC algorithms used for the Shuttle's ascent and orbit, which could run autonomously or with crew control capabilities. We also provided additional software for ground alignment and gyro-compassing, as well as fault detection for the thrusters, Orbital Maneuvering System engines and gimbals, and the three redundant IMUs.

After the Shuttle entered operational service in 1981, Draper continued to provide technical support for the flight control system, including numerous upgrades to the GNC software that improved safety, enhanced future mission operations, and reduced operational costs. Updates to the landing and rollout flight control algorithms and systems helped avoid potential pilot-induced oscillations and provided increased margins for landing at the Kennedy Space Center. To improve launch capability, our engineers developed software to allow for near-real-time determination of first-stage trajectory parameters.

Draper supported the Space Shuttle Program continuously until its end in 2011—developing a series of on-orbit flight control system upgrades in later years to support the complex operations required to control and deploy large payloads, repair and service the Hubble Space Telescope, dock with the *Mir* Space Station, and assemble the International Space Station.

STS-135, the final mission of the Space Shuttle program, launched on July 8, 2011.



The International Space Station

THE INTERNATIONAL SPACE STATION

In 1987, while Draper was still supporting the Shuttle program, we began work on Space Station Freedom, which was eventually superseded by the International Space Station (ISS). Draper was instrumental in developing the initial Station-wide Data Management System (DMS) and later developed the early flight control system, which was an alternative approach to the DMS design. Draper also designed the fault-tolerant architecture that integrated all avionics functions across Freedom and ensured that the fault-tolerance requirements were met for all stages of assembly. These design approaches became the foundation of the ISS fault-tolerant avionics design.

After the ISS program was created, Draper conducted extensive analysis and design of the interaction between the control thrusters and the flexible station structure—also known as the control-structure interaction. Our control algorithms reduced loads on the structure during maneuvers powered by either Station or Shuttle thrusters. Draper also applied our Timeliner™ software, developed previously to emulate the pilot in the Shuttle simulations, to provide the user interface for all critical commanding of the Station and the experiments/payloads. With its natural language interface, Timeliner was able to store and execute complex sequences of commands, reducing astronaut workload and the opportunity for errors. In addition, our engineers performed dynamic interaction analysis in support of Shuttle payload operations, including those involving the highly flexible Canadian Remote Manipulator System.

Since its first expedition in 2000, Draper has contributed to the operational success of ISS in numerous ways. In 2006 and 2007, ISS employed a Draper-invented technique known as the Zero Propellant Maneuver to conduct large-angle maneuvers without the use of its thrusters. Akin to a sailboat tacking against the wind, the maneuver relied on gravity and aerodynamics. By 2012, Draper had evolved the technique into what became known as the Optimal Propellant Maneuver, modifying the algorithm to accelerate rotation and ensure that ISS maintained its thermal, power, and communications constraints. Used twice that year, the optimized maneuver demonstrated a 90% savings in fuel, dramatically reducing operating costs and extending the Station's usable life.

Beginning in 2009, Draper's differential mobility spectrometry technology provided continuous, real-time monitoring of air quality on the ISS. Capable of detecting trace levels of volatile organic compounds, our microAnalyzer™ could be operated via wired or remote communication. In January 2015, incorrect pressure sensor readings from a coolant system signaled a potential ammonia leak, forcing the astronauts to shut down nonessential equipment and evacuate the U.S. module. From the ground, controllers were able to operate the microAnalyzer and confirm that the air was safe to breathe, allowing the astronauts to return safely to the U.S. module.

After the Space Shuttle retired in 2011, Draper supported multiple programs focused on uncrewed resupply of the ISS, providing autonomous GNC software and fault-tolerant computers. Today, we remain a valuable partner for U.S. missions aboard the ISS, providing ongoing support for Timeliner, which is used to develop code bundles and scripts that automate on-orbit operations.

ARTEMIS

By 2005 NASA was eyeing a return of crewed spacecraft to the Moon, and Draper led or supported key efforts under the precursor programs that were eventually folded into the Artemis program. Under the Constellation program, our engineers supported the NASA Design Team that developed the upper stage and instrumentation unit of the Ares I launch vehicle. Its complement, the Ares V, later became the Space Launch System (SLS).

Draper contributed to development of the SLS in the areas of flight software development, control systems design (including vehicle flex and slosh control), guidance system design, and avionics systems engineering. Based on trade studies conducted during the Ares I development between X-38-like flight computers and a software-based approach, NASA selected software-based redundancy management. The software developed for flight was based on work originated by a Draper Scholar and flew successfully on the Artemis I mission, demonstrating Draper's evolving approach to flight computer redundancy management.

For the Orion exploration capsule, we developed numerous systems and technologies, including the GNC flight software for navigation, solar array controls, orbit and skip guidance, mission management, and fault detection. Draper supported simulation development, led validation and verification of the GNC system and hardware in the loop, and supported Mission Evaluation Room operations.

When Congress cancelled the Constellation program in 2010, the Orion and SLS programs survived, and Draper engineers provided continuity of support across several key milestones. Our enhanced skip entry approach successfully landed Orion in the Pacific Ocean during its 2014 engineering flight test. During Orion's 2019 abort test, the Launch Abort System powered by Draper's GNC software demonstrated that it could steer the capsule to safety if an emergency occurs during ascent—effectively clearing NASA's final testing hurdle in preparation for crewed missions to the Moon and beyond.

In 2020, Draper sensors and software flew aboard Blue Origin's New Shepherd craft, gathering data to better understand the range of operations required for a future lunar descent and landing. That same year, Draper was part of two teams—led by Blue Origin and Dynetics, respectively—selected to develop and demonstrate a Human Landing System (HLS) to support future lunar missions under Artemis. In support of these efforts, our engineers developed human-rated avionics, including precision navigation and guidance systems and software. We also developed avionics architectures, demonstrated landing computer redundancy management, developed cockpit displays and controls, and developed advanced motion based simulators. Our human-systems engineers helped develop the HLS flight deck, and we designed manual control software for reliable and safe operation by crewmembers.

In 2018, Draper joined NASA's Commercial Lunar Payload Services (CLPS) program, leading an industry team to develop an autonomous lander capable of delivering payloads to the lunar surface.

In November 2022, SLS successfully launched Orion on its Artemis I mission from the Kennedy Space Center. Orion's solar arrays deployed and the capsule completed two lunar flybys before splashing down in the Pacific Ocean on December 5. The success of this uncrewed mission marked a major milestone toward the long-awaited return of humans to the Moon, certifying SLS and Orion for future crewed flight on Artemis II.

Under the Artemis umbrella, Draper's long history of enabling NASA's human space missions reaches well into the future. In 2021, NASA renewed our longstanding contract to develop and test advanced GNC and avionics technologies for the agency's next generation of human-rated spacecraft on missions beyond low-Earth orbit.

Today, Draper engineers are working on technologies necessary for the follow-on Artemis missions—including the Gateway outpost, human landers, and lunar terrain vehicles, which will require sophisticated controls and displays for onboard crewmembers and will advance NASA's lunar landing and exploration capabilities.

SATELLITES AND SCIENCE MISSIONS

Draper's historic contributions to the exploration of space span important science and technology missions, as well as the uncrewed missions that pave the way for humans to return to the Moon and beyond. We engineered numerous breakthroughs in autonomous systems, developed advanced GNC for launchers, and provided rad-hard microelectronics for the Parker Solar Probe to ensure that its sensitive instruments would function even under extreme conditions near the Sun.

We have also designed highly customized instruments to support NASA's Science Mission Directorate. For example, NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE), which launched in 2013, featured an ultraviolet and visible light spectrometer built by Draper. LADEE orbited the Moon for about six months, gathering data about the structure and composition of its atmosphere by analyzing light signatures. Draper's technology revealed that the lunar atmosphere is largely comprised of helium, neon, and argon, confirming theories that had been under speculation since Apollo.

In 2016, Draper-developed GNC technologies guided eight microsatellites into orbit, ushering in a new era of weather science and forecasting. Under NASA's Cyclone Global Navigation Satellite System (CYGNSS), we developed a unique attitude determination and control system to provide closed-loop functionality for the CYGNSS spacecraft—including stabilization, Sun acquisition and hold, pointing control, and momentum management. Originally slated for a two-year mission, CYGNSS provided nearly gap-free coverage of Earth through 2022, providing data on hurricanes, typhoons, and tropical storms and enabling detection of flooding on land and microplastic debris in the ocean.

In 2018, Draper joined NASA's Commercial Lunar Payload Services (CLPS) program, leading an industry team to develop an autonomous lander capable of delivering payloads to the lunar surface. Designed with modular bays, our CLPS lander will be capable of delivering up to 3,050-kg payloads to lunar orbit and up to 1,150 kg to the surface. Capable of surviving lunar night, the Draper team's lander will be able to navigate to precise landings and avoid hazards en route. Because there is no line of sight from the landing site back to Earth, our team is also deploying relay satellites to support high data transmission rates and continuous ground communications.

In 2022, Draper was awarded a contract to deliver three NASA-funded science payloads to Schrödinger Basin. Slated for 2025, this mission will mark the first U.S. trip to the Moon's far side.

COMMERCIAL SPACE MISSIONS

Under government-funded programs, Draper has partnered with virtually every major private-sector company that engineers and manufactures space vehicles—including launchers, landers, and orbiters—for science missions, cargo transport, and crewed flight. As NASA retired the Space Shuttle and turned to private industry to develop alternatives for crewed space missions, Draper became a highly sought-after partner for our unparalleled expertise in fault-tolerant computing, precision guidance, sensors and systems engineering, and electronics instrumentation.

In 2018, our experts began supporting development of a commercial two-stage launch vehicle that will be used to deliver astronauts and payloads to a range of Earth orbits. Our support spans GNC; fault detection, isolation, and recovery (FDIR) analysis; independent verification and validation of algorithms and simulation models; flight software process evaluation; and high-fidelity simulation integration activities. That same year, ispace engaged Draper to provide descent GNC for its HAKUTO-R lunar program. Launched in 2022, the Mission 1 lander will attempt a landing in the spring of 2023, setting the stage for ispace to provide high-frequency, cost-effective transportation to the Moon.

In support of a commercial, suborbital launch vehicle designed for high-altitude experiments and space tourism, in 2019 Draper engineers developed test cases and provided results and documentation to verify the flight software running onboard the launch vehicle. That year, we were also contracted by a commercial space company to help qualify the first stage engine for a two-stage launch vehicle. Our team provided expertise in systems engineering, electronics hardware, software verification, and simulation models. By 2023, the engine qualification had reached the final phases. Draper also helped mature engine and mechanical designs for the vehicle's second stage and a lunar lander and performed radiation testing of electronic components.

In 2020, we were engaged by a commercial space company to develop model-based methods to continuously integrate and iterate mission design in support of its lunar lander mission. Our work includes supporting mission and crew operations planning. We lead the Model-Based System Engineering (MBSE) approach for the program from the ground up, developing methods and analyses to support decision making and mission timelines. By integrating with the mission design models, Draper has created an integrated concept of operations tool to decompose the mission and validate constraints—from pre-launch to completion of the mission.

Also in 2020, Stratolaunch contracted Draper to develop and test advanced GNC algorithms and flight software for its hypersonic Talon-A vehicle. Designed for speeds up to Mach 6, Talon-A is a reusable, liquid rocket-powered craft intended to serve as an affordable test bed for hypersonic research and experiments and to support operational missions. In 2022, Stratolaunch completed its first captive carry flight with the Talon-A—marking Draper's inaugural success in a hypersonic flight envelope.

In 2022, Draper began supporting a commercial space company in defining the behavior of one of its platforms using model-based methods. These methods have helped identify use cases and design reference missions for the customer.

LOOKING AHEAD

Draper has a long heritage of applying critical technologies to space systems, partnering with NASA and industry in the development of these technologies and their application. The wealth of this experience and lessons learned informs and enables the next generation of space systems, including application to commercial space programs and national security.

Some of our most ambitious projects focus on enabling robotic and human landing missions at challenging sites of significant scientific and commercial interest—including the Moon, Mars, asteroids, and outer planet moons. Draper also aims to develop innovative autonomy capabilities that will reduce the cost of deep space, small satellite missions by requiring less oversight from Earth.

Our experts in human-machine teaming are conducting foundational research to enable more synergistic crew/machine operations in space, and we continue to advance the precision navigation technologies that first carried humans to the Moon—with an eye toward the farthest reaches of our solar system.

In 2010, the National Aeronautic Association awarded Draper the Collier Trophy, the nation's top aerospace award, for its role on the ISS team. Left to right: Phil Babcock, Vice President Darryl Sargent, President Jim Shields, Bob Brown, Doug Zimpfer, and Seamus Tuohy.

Draper developed a lunar landing simulator to celebrate the 50th anniversary of the Apollo 11 landing and to serve as a test bed for future pilot display and control capabilities.

CHAPTER 6

Draper developed its All-Domain Execution and Planning Technology framework for intelligent autonomous systems under DARPA's Advanced Minehunting and Mapping Technologies program and first tested it in 1996.

From Autopilots to Intelligent Autonomy

VEHICLES AND ROBOTS FOR ANY MISSION

Beginning in the 1950s and '60s, Draper made its first forays into the field of autonomy, developing autonomous guidance systems for the Apollo missions and the U.S. Navy's submarine-launched ballistic missiles. Drawing on this legacy of highly reliable performance for time-critical, complex applications, in the 1980s we embarked on what would eventually become a robust, multidomain portfolio of autonomous systems R&D, production, and delivery.

The first autonomous systems performed missions that were largely scripted, functioning as an autopilot that executed preplanned actions based on anticipated events. From there, our capabilities evolved to include human-supervised autonomous systems that allow the mission sequence to evolve and intelligent autonomy systems that can execute abstract human directives and adapt to unplanned events—without additional input from the operator.

Autonomy is a multidisciplinary field, demanding a broad range of expertise that spans Draper's unique strengths in software and hardware—from foundational planning frameworks and complex algorithms to interfaces, integrated sensors, simulation environments, and models. Through internally funded and government-sponsored R&D, our engineers have significantly advanced the state of the art—designing, validating, and demonstrating increasingly intelligent autonomous systems.

Draper's Maritime Open Architecture Autonomy successfully controlled a Navy Snakehead vehicle during field testing in 2022.

A VERSATILE FRAMEWORK FOR AUTONOMOUS MISSION PLANNING AND EXECUTION

Through a series of projects funded by NASA, DARPA, and the Office of Naval Research, Draper developed, implemented, field-tested, and advanced a closed-loop, hierarchical, real-time planning software architecture that could reason about its environment, responding to unexpected events in real time and replanning missions as needed.

First developed and tested under DARPA's Advanced Minehunting and Mapping Technologies (AMMT) program in 1996, our All-Domain Execution and Planning Technology (ADEPT) provided a novel framework for developing intelligent autonomous systems. ADEPT manages the performance of the entire vehicle, from system-level mission objectives to subsystem-level health and monitoring. Using this framework, Draper decomposes mission operations temporally and functionally—from the mission level down to the individual vehicle subsystems. At each level, ADEPT executes the optimal plan, monitors for deviations from expected results, and develops a new plan as needed to address such deviations.

Early on, Draper engineers recognized the counterintuitive fact that operators are an important component of any autonomous system—by setting mission objectives, monitoring progress, and/or actively redirecting the mission in real time. Thus, the ADEPT framework incorporated approaches that allowed for the decomposition of complex, high-level instructions (i.e., commander intent) to multiple levels of a planning system. In addition to creating tractable and easy-to-understand plans, this approach also provided the operator with visibility into what was happening at each level of the hierarchy.

Over the years, Draper has applied the ADEPT framework across domains—air, space, ground, and undersea—incorporating next-generation technologies for better performance. Today's ADEPT framework supports the full range of mission-specific capabilities, enabling real-time mission management by creating trajectories, identifying and avoiding obstacles, and recognizing and tracking targets. Our software engineers have successfully evolved ADEPT from a laboratory framework to a field-demonstrated platform that is modular and extensible, applying it on prototype ground and air vehicles and commercial off-the-shelf drones and scaling it under DOD programs of record.

AUTONOMOUS UNDERWATER VEHICLES (AUVS)

In the late 1980s, Draper was selected to lead DARPA's first explorations into autonomous underwater technologies as part of the agency's Unmanned Undersea Vehicle (UUV) Rapid Prototyping program. Our engineers built and field-tested two long-duration, uncrewed vehicles to develop and demonstrate key UUV technologies and prove the utility of autonomous undersea operations for the DOD. The vehicles had triply redundant processors for reliable long-term operations, with a modular design that could support multiple disparate payloads and missions.

In the mid-1990s, Draper implemented our ADEPT architecture as part of DARPA's AMMT program, which combined precise navigation, adaptable vehicle maneuvering, long-range acoustic communications, and undersea imaging to enable autonomous mine and obstacle detection. At the time, ADEPT extended DARPA's existing UUV capability with real-time dynamic replanning to adapt the mission plan to real-time, off-nominal disturbances that arose during execution.

A series of efforts followed AMMT that matured undersea autonomy technology through demonstration-focused science and technology programs. In 2003 and 2004, we designed and implemented an autonomous controller capable of increasing levels of mission complexity as part of the Navy's Maritime Reconnaissance Demonstration system. Designed to gather signal intelligence, these UUVs successfully identified, assessed, and avoided nonhostile surface traffic and ground- and air-based hostile threats, while continuously evaluating whether to complete or abort the mission.

One key outcome of this work was Draper's Maritime Open Architecture Autonomy (MOAA)—a modular, extensible, and vehicle-independent development framework based on ADEPT. In 2012, MOAA became the de facto Navy standard and was made available to the UUV community of interest as government open-source software. As a result, MOAA has been used on small, medium, and large vehicle classes.

Draper's innovation with MOAA continues as we migrate to a scalable, service-oriented architecture. This will support rapid deployment of MOAA onto new platforms at scale, further cementing MOAA's status as the leading approach for undersea autonomy solutions capable of complex, long-endurance missions.

Delivering reliable undersea autonomy that is resilient to challenges encountered over long durations also requires innovation in operator mission planning and the use of simulation for mission verification. Since 2013, Draper has successfully matured two additional technologies in the undersea domain to ensure reliability of autonomy solutions.

Our Scalable UxV Mission Manager (SUMM) is a graphical user interface for planning complex, long-duration missions. In developing SUMM, Draper leveraged expertise in human centered engineering and human systems integration to create an intuitive interface that reduces the time required to generate such missions.

Building on the Draper Simulation Framework originally developed for strategic guidance programs, our engineers created the Undersea Digital Simulation (DSIM) platform. DSIM is a high-fidelity, six-degree-of-freedom, physics-based framework that has served as the lynchpin for ensuring that our MOAA-based and other autonomy solutions are robust and reliable. Across numerous projects, we developed modular ocean environment, vehicle, and sensor models in DSIM—enabling our teams to validate autonomy solutions for AUVs and significantly reducing the cost, schedule, and risk associated with testing systems in the field. DSIM's demonstrated modularity, fidelity, and benefits led to its expanded usage. Today, it has become a key tool in Draper's model-based systems engineering process for evaluating modular AUV designs, as well as for developing digital twins that can support operational deployments.

As these products mature, Draper continues to innovate by closely integrating mission planning, autonomy, and simulation. This enables the undersea community to quickly design and optimize complex, long-duration missions for AUVs. In 2022, the Navy's Snakehead large displacement vehicle was successfully tested under MOAA control on its first day in water. The tight integration of Draper-developed innovations supported an accelerated—and successful—test program with more than 100 MOAA-executed sorties in water that had initially been verified by hundreds of hours of simulations in DSIM.

Draper will continue to advance autonomous systems for undersea missions such as mine countermeasure, exploration, intelligence, surveillance, and reconnaissance—with a view toward enhancing our nation's warfighting capabilities well into the future.

Draper's SAMWISE algorithm provides GPS-denied navigation capabilities, enabling small, low-cost drones to fly high-speed reconnaissance missions autonomously in cluttered environments.

AUTONOMOUS NAVIGATION WITHOUT GPS

Reliance on GPS for navigation presents a significant vulnerability for an autonomous vehicle. If the vehicle loses the signal for any reason, it can stray off course or crash, confounding the mission and potentially putting sensitive military technology at risk. Under a series of DOD contracts beginning in the mid-2010s, Draper engineered significant breakthroughs in vision-aided navigation—including technologies for absolute and relative positioning—to solve this challenge. Vision-aided navigation (VAN) employs cameras and other sensors to minimize the drift associated with navigation by inertial measurement and to enable navigation without the reliance on GPS.

In 2014, the U.S. Army sought to augment its GPS-dependent autonomous airdrop capabilities—known as the Joint Precision Airdrop System (JPADS)—with the ability to navigate based on visual aids. Draper had a long history of support for JPADS, having provided the original GNC for its first operational use in Afghanistan in 2006. Draper's GPS-denied navigation system for JPADS combines visual odometry, visual terrain relative navigation (TRN), and altimetry data to produce a reliable, globally referenced navigation solution.

By 2016, Draper had demonstrated our algorithms in closed-loop test flights, including image-based absolute localization (IBAL) and our Lost Robot initialization algorithm, which enables 100% GPS-denied flight. IBAL uses a camera to compare objects seen against pre-loaded images of the environment. These measurements are provided to Draper's Yeti vision-aided navigation system to produce robust, unjammable navigation solutions. Still underway today, the JPADS program called for rigorous testing—three or four tests each year, with 20 flights per test.

Draper engineers applied that experience under DARPA's Fast Lightweight Autonomy (FLA) program— which began in 2015—to develop a new VAN algorithm called SAMWISE. Similar to Yeti, SAMWISE produces low-latency position, velocity, and attitude estimates by combining the advantages of vision and inertial sensing. SAMWISE reduced the known drift of both techniques when used alone, and it can work with a variety of sensors/data sources, including GPS, cameras, and light detecting and ranging (LiDAR). Combined with an aggressive motion planner and obstacle detection system, SAMWISE enabled small, low-cost drones to fly high-speed reconnaissance missions entirely autonomously through obstacles like buildings and forests. We also integrated communications with the Tactical Assault Kit (TAK) platform, enabling the unmanned aerial vehicles (UAVs) to send images to a mobile device and overlay the locations of detected objects of interest on a satellite map for human team members—all in real time.

The success of our VAN solutions for UAVs led to numerous projects that explored the suitability of these algorithms for space applications. When developing VAN for space, testing presents a major challenge because images available prior to the mission may not represent the conditions that the algorithms must process in-flight. Drawing on our experience developing and testing algorithms for terrestrial applications, Draper was able to design testing strategies to mitigate these risks. For lunar precision landing, this included simulation capabilities and several flight tests to demonstrate Draper's VAN algorithms in conditions that are representative of lunar trajectories.

Draper developed the original flight software for the Joint Precision Airdrop System (JPADS) and continues to develop new capabilities for the system, including the ability to navigate autonomously in GPS-denied environments.

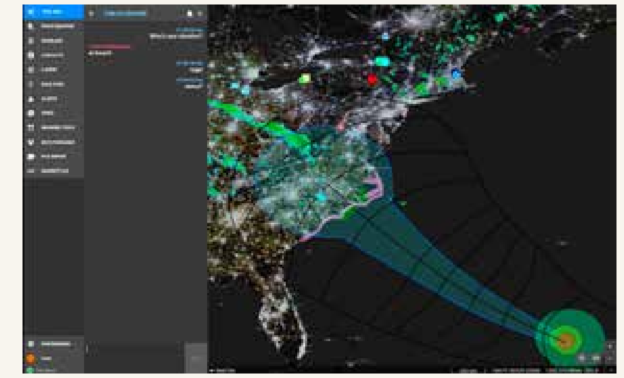
In 2019, the Draper Multi-Environment Navigator (DMEN) successfully completed a test flight on a high-altitude balloon under conditions that matched high-altitude space orbits more closely than the JPADS flight profiles. As the balloon rose to an altitude of 108,000 feet, DMEN used optical sensors to spot terrain features and compared them to commercial satellite imagery of the area. That same year, under NASA's Safe and Precise Landing Integrated Capabilities Evolution (SPLICE) project, our TRN system flew aboard a Masten Xodiac rocket and successfully identified ground features under dynamics more representative of spacecraft motion. The following year, during another test flight under SPLICE, Draper successfully demonstrated IBAL at altitudes of up to 100 km aboard Blue Origin's New Shepherd suborbital rocket.

In addition to testing, the accuracy of a TRN system hinges on its ability to recognize terrain features which, in turn, depends on the feature models programmed into the system. In 2020, Draper's expertise in feature robustness for autonomous navigation was critical to the successful touchdown of OSIRIS-REx on the asteroid Bennu. With a touchdown site only 26 ft wide, Bennu's rocky surface demanded a high degree of precision. Draper selected the strongest terrain features and worked closely with NASA, Lockheed Martin, and the science team to build, test, and refine shape models on which the spacecraft's Natural Feature Tracking system relied.

Draper further advanced our TRN capabilities through development and testing in 2021 and 2022 under NASA's Human Landing Systems (HLS) program. By testing in relevant flight environments with realistic hazards, Draper aims to integrate TRN and visual odometry into a single vision-aided navigation and hazard detection system for safe and precise lunar landings under future civil and commercial missions.

Draper has also configured our SAMWISE vision-aided navigation solution as a Wearable Kinematics System (WKS) that may one day help Artemis astronauts safely explore lunar craters. Originally designed to study the 3D motion of humans aboard the International Space Station, the WKS allows the wearer to map their environment, track position and orientation, and monitor time on task. Draper successfully tested the system underwater during NASA's 2019 Extreme Environment Mission Operations (NEEMO) expedition and again in 2022 on a simulated moonscape in the Arizona desert.

Closer to home, Draper has explored technologies to outfit driverless cars with vision-aided navigation. In 2018, we successfully demonstrated a LiDAR system that can see in all weather conditions, including rain, snow, and dense fog. Designed to augment the LiDAR systems used in current self-driving vehicle applications, our Hemera LiDAR technology may one day make safe, reliable autonomous navigation a feature of daily life.



Draper developed a web-based version of the Tactical Awareness Kit called WebTAK.

ENABLING TECHNOLOGIES FOR TACTICAL COMMUNICATIONS

One of Draper's signature contributions to the military's UAV programs—and to defense readiness in general—is a suite of georeferenced imagery and communications tools known as the Tactical Assault Kit (TAK).

Originally conceived by U.S. Special Operations Command (SOCOM) operators in 2006 and formalized by the US Air Force Research Laboratory (AFRL) in 2010, TAK expanded to include a robust suite of capabilities for close air support, navigation, sensor feeds, and drone control. With TAK, operational teams can collaborate, share data, and manage mission targets—all from modern handheld devices. In addition to human-to-human networking, TAK enables human operators to communicate with sensor systems and autonomous vehicles. To develop the operator interface, Draper created a novel framework for human machine teaming, integrating best practices in human-centered design and engineering.

By 2013, TAK was in use by Special Operations. The software entered mass deployment in 2014 and—with Draper support—has since been adapted for law enforcement, security, and emergency response scenarios. For example, in 2018 rescue and relief operations after Hurricane Florence relied on a version of TAK for real-time communications and networking—including live video feeds, personnel tracking, site surveys, geospatial mapping, navigation, and chat. Today, the suite of platforms provides situational awareness for more than 250,000 active warfighters, national security personnel, and civilian users.

From 2013 through today, Draper has provided development, maintenance support, technical services, testing, evaluation, and training for the TAK suite on behalf of various DOD sponsors. In 2022, the Draper-developed WebTAK version became SOCOM's identified solution for real-time decision support, situational awareness, and crisis response and communication. That year, we began work in collaboration with Skyline Nav AI to enable the Android version of TAK to provide accurate localization even in GPS-denied environments—a mission-critical capability for the modern warfighter.

Through these and other efforts, Draper aims to ensure that TAK continues to deliver situational awareness and a decision advantage to warfighters at the tactical edge.

AERIAL VEHICLES

The development and successful fielding of Draper's autonomous undersea vehicles led to opportunities to develop similar capabilities for small unmanned aircraft. In the 1990s and early 2000s, Draper participated in a series of projects with DARPA to apply mixed-initiative, closed-loop, optimization-based planning and control technology to increasingly complex scenarios. By 2016, those scenarios included dodging obstacles in cluttered environments, at high speeds, and without a GPS signal under DARPA's Fast Lightweight Autonomy (FLA) Program.

In 2019, the military's Joint Program Executive Office engaged Draper to develop UAVs under its Chemical Biological Radiological and Nuclear (CBRN) Sensor Integration on Robotics Platforms (CSIRP) program. CSIRP calls for rapid prototyping and field testing of small UAVs capable of flying low-altitude missions to identify CBRN threats. To achieve the program objectives, Draper leveraged the full breadth of our capabilities, including the ADEPT framework, SAMWISE vision-aided navigation, the dynamic path planning and obstacle avoidance developed under FLA, and integration with the TAK communications platform.

The result: a multi-agent, multi-domain system of highly agile aerial drones and ground-based robots. Our CSIRP solution functions even in GPS-denied environments, providing soldiers with a map-based common operating picture and enhanced situational awareness for command and control.

Initially envisioned as a completely autonomous system, CSIRP field tests revealed that operators preferred to retain some control to re-task the system or abort the mission as needed. Our human-systems engineers worked with military operators to define those parameters and deliver a system that met their needs.

Today, our engineers are integrating CSIRP autonomy into the SkyRaider UAV, further extending and operationalizing this capability for use in the field. The CSIRP program epitomizes Draper's vision of success: moving a technology from the exploratory R&D stage, through rapid prototyping, adaptation, and optimization for complex real-world missions, and culminating in upcoming integration and production under a DOD program of record to support our nation's warfighters.

Under DARPA's Orbital Express program, a Draper team worked with Ball Aerospace to conduct a demonstration of on-orbit satellite servicing, including refueling and avionics replacement.

SPACECRAFT

From the first significant demonstrations of autonomous space vehicles through our innovations in terrain-relative navigation, Draper has played a major role in advancing autonomy for a wide variety of space missions. In addition to back-up landing systems for crewed missions, we have developed systems for fully autonomous vehicles to launch, orbit, navigate, and land in support of exploration, science missions, and cargo transport.

In the early 2000s, Draper developed a suite of algorithms to reconfigure large numbers of Earth observation satellites. Our Earth Phenomena Observation System (EPOS) maximized the value of Earth science and was later adapted for the intelligence community. We also supported development of AFRL's Experimental Satellite System-11 (XSS-11). Launched in 2005, the XSS-11 was designed to test and verify technologies to enable safe and autonomous rendezvous with and inspection of other space objects. Two years later, DARPA's Orbital Express program demonstrated the ability of an autonomous craft to service a satellite in orbit, including transferring propellant and replacing a computer processor. Draper's Timeliner™ software was a critical component of this mission, allowing automated sequencing and process control using natural language.

In 2010, under NASA's Autonomous Landing and Hazard Avoidance Technology (ALHAT) Program, our engineers designed and built an autonomous avionics system—dubbed the Guidance Embedded Navigator Integration Environment (GENIE)—in only seven weeks. In 2012, GENIE successfully controlled a suborbital rocket during a closed-loop tethered flight, marking the first terrestrial demonstration of an autonomously guided rocket flying a planetary landing trajectory. By enabling realistic testing of landing maneuvers on Earth, Draper's technology helps raise the overall Technology Readiness Level of emerging space technologies.

Our work on GENIE and hazard detection technologies under ALHAT provides a strong foundation for Draper's role on NASA's Commercial Lunar Payload Services (CLPS) program. In 2018, NASA selected Draper to support efforts under CLPS to develop autonomous lunar landers for science and exploration missions in preparation for future crewed missions planned under the Artemis program. Our prime role on CLPS CP 12, awarded in 2022, is a credit to our deep roots and broad technology presence in the space sector—and particularly in autonomous GNC.

By 2021, Draper had begun adapting our ADEPT framework to provide mission planning, guidance and control, real-time monitoring and response, and abort and replanning for space missions. As NASA seeks to foster a robust private space industry, Draper will continue to deliver the autonomy required for safe and cost-effective missions.

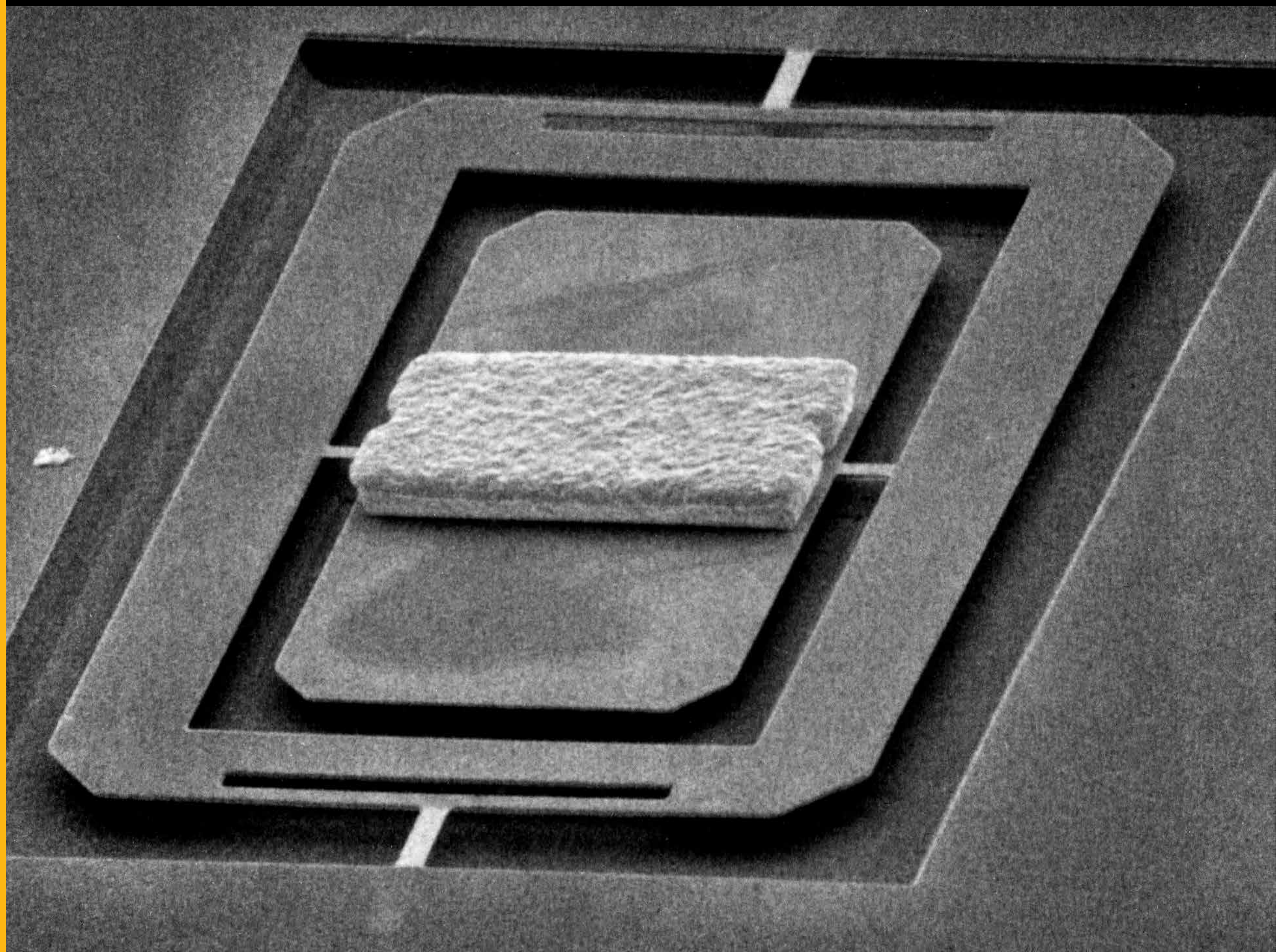
LOOKING AHEAD

As Draper engineers build on our portfolio of innovative autonomous systems, we will continue to evolve our modular ADEPT framework to meet emerging needs for military, space, and civil missions.

We expect this to include more scenarios that, like CSIRP, require multi-agent and multi-domain solutions: autonomous vehicles and robots that can collaborate—on the ground, in the air, under water, or in space—and can function in highly complex, contested, and congested environments. Our most forward-looking research today seeks to fuse AI and machine learning into our solutions to better understand the operating environment, tie predictive data into navigation or operator displays, and engineer autonomous systems to inspire human trust.

Ultimately, we envision a future state where multiple autonomous vehicles and their human counterparts work together as a team—leveraging the complementary strengths of humans and machines to adapt to the evolving needs of government, industry, and the warfighter.

(CHAPTER 7)



Draper's revolutionary silicon "double-gimbal" gyro design

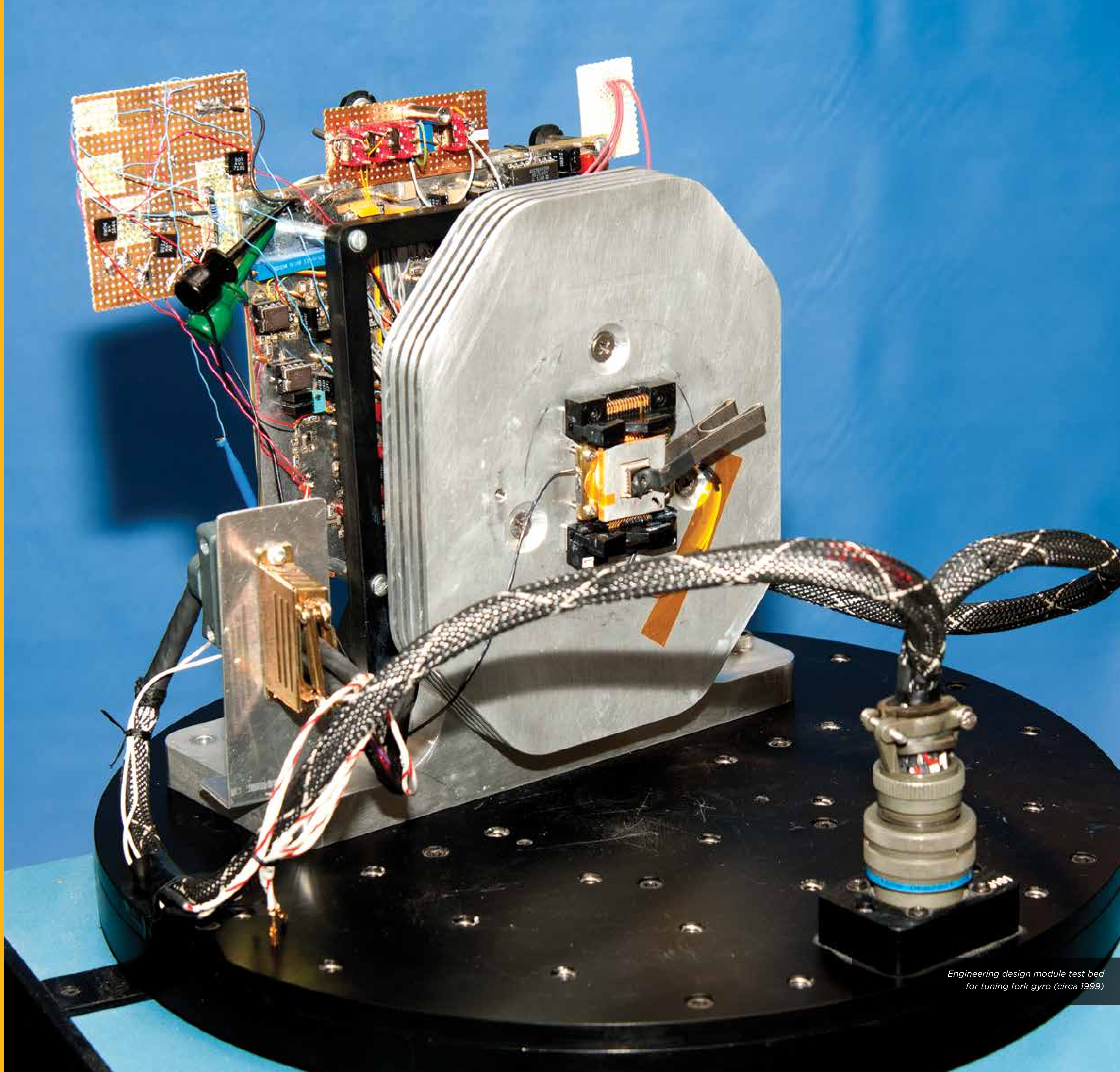
Microelectronics

HOW SMALL SYSTEMS AND ADVANCED PACKAGING ENABLE BIG TECHNOLOGY SOLUTIONS

Draper's expertise in ultra-miniature sensors and systems can be traced to pioneering work in new sensors for GNC. In the early 1980s, engineers Burton Boxenhorn and Paul Greiff were looking for ways to achieve smaller, lower-power inertial instruments. They developed an idea for a miniature vibrating gyroscope after reading an article about the sensory-motor abilities of flies. They noted that flies sense their rotation during flight using vibrating structures called halteres to detect body rotations via gyroscopic forces.

Inspired by the fly's halteres, they envisioned a microscopic gyroscope, fabricated by processes borrowed from the semiconductor industry to build 3D structures out of silicon. The sensor they envisioned would have many advantages. Featuring a size of only a few microns, it would be very small and lightweight, enabling many previously unguided systems to carry an active GNC system. It also would be very robust, able to tolerate very high g loads. Most important of all, it could be constructed using large-scale manufacturing techniques pioneered by the semiconductor industry, which meant that it potentially could be much lower in cost than existing systems.

In 1987 their microelectromechanical systems (MEMS) gyro design, etched from a silicon wafer, was the world's first to sense rate, and their first monolithic silicon gyro was demonstrated in 1991. This was the first of many pioneering achievements in miniature systems made at Draper over the next 30 years using both MEMS sensors and the corresponding electronics—with applications spanning a wide variety of uses, including inertial sensing, precision timing, microphones, vibration sensors, chem/bio sensors, tissue engineering, radiation-hardened electronics, and strategic-grade packaging.



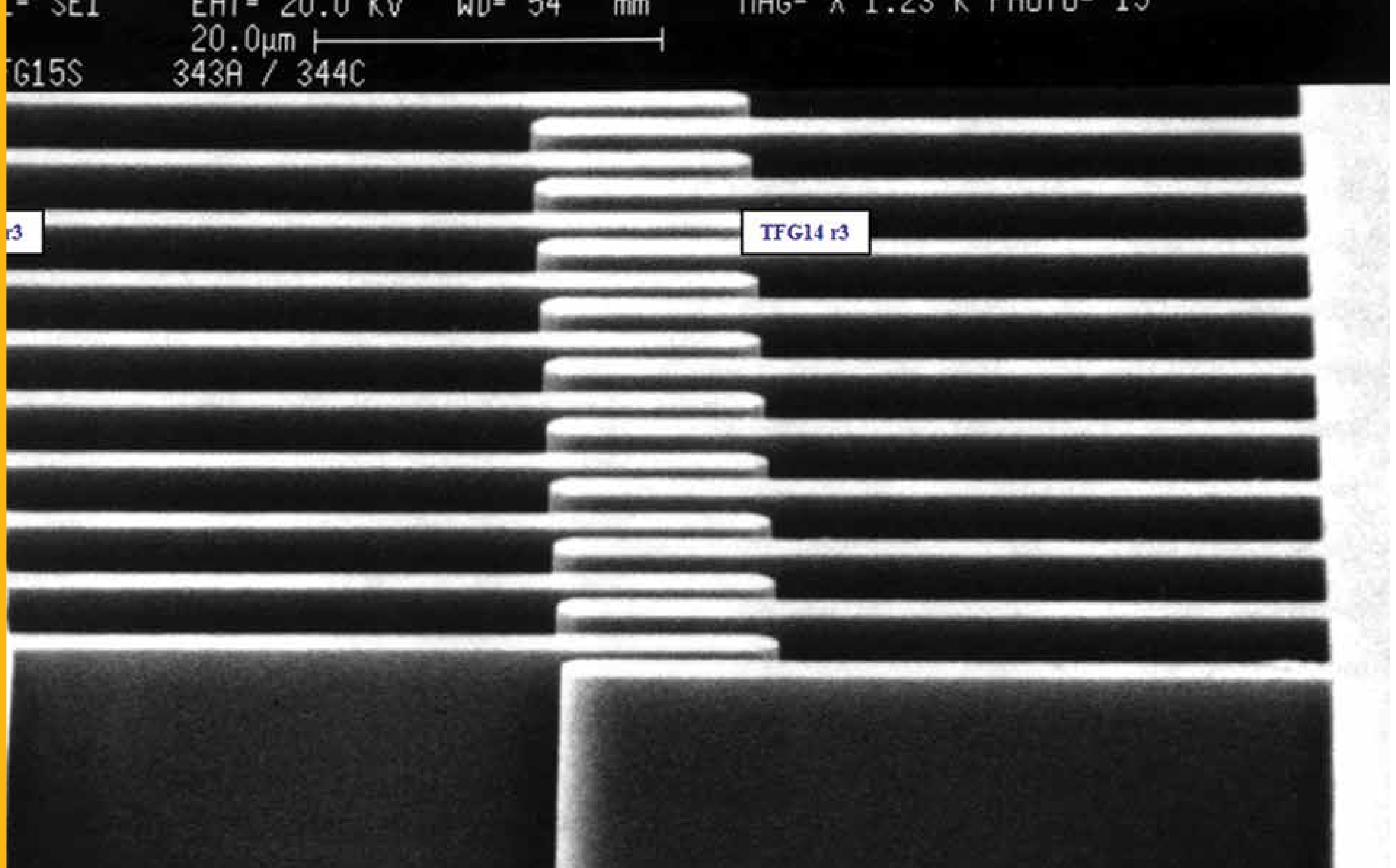
Engineering design module test bed for tuning fork gyro (circa 1999)

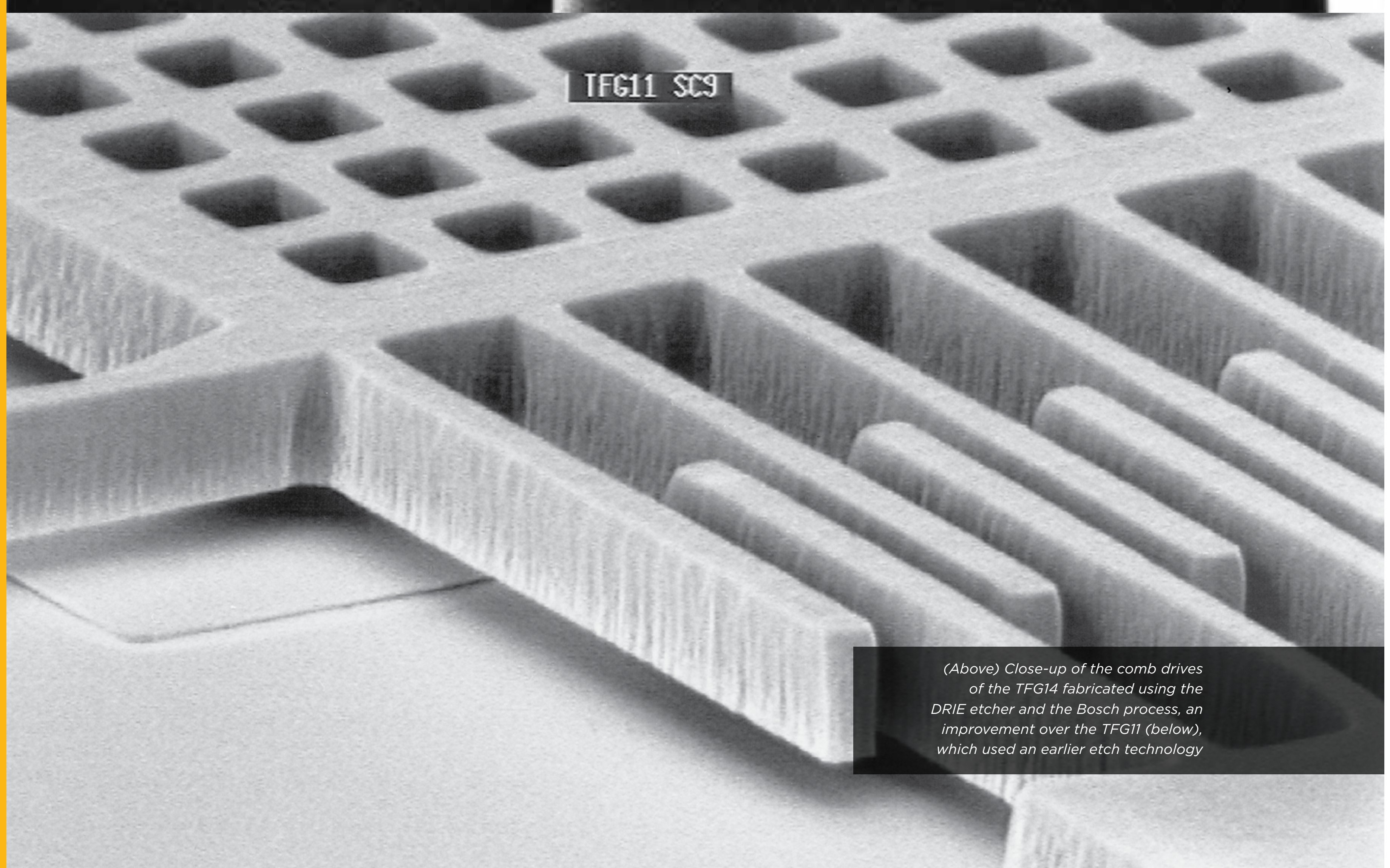
The MEMS technical team in 1996

Draper formed a large team to capitalize on Boxenhorn and Greiff's idea, an expanded silicon processing facility was constructed, and new researchers were brought on. Over the years, this team was supported by a combination of Draper independent research and development (IRAD) funding and sponsored projects. This technology area marked our most significant investment since separating from MIT and is an outstanding example of how Draper uses fees earned from government contracts to advance technology in the national interest.

Advancements in fabrication techniques and sensors of all types followed at a dizzying pace. Marc Weinberg led the design team and proposed a tuning-fork gyro (TFG) design, featuring a pair of in-plane, resonant, vibrating proof masses, whose out-of-plane motion was proportional to angular rate. Jonathan Bernstein made the TFG feasible by leveraging the electro-static comb drive technique developed at the University of California, Berkeley.

The last key piece of the silicon gyro sensor puzzle fell into place months later, when Steve Cho joined Draper from the University of Michigan and brought the dissolved wafer process in-house. This simple, three-step, batch fabrication technique enabled low-cost, high-volume production of MEMS sensors, giving Draper the tools to explore many practical government and commercial applications.





(Above) Close-up of the comb drives of the TFG14 fabricated using the DRIE etcher and the Bosch process, an improvement over the TFG11 (below), which used an earlier etch technology

THE DARPA CONNECTION

An important government funding opportunity in this area occurred when DARPA established DOD's flagship MEMS program in 1992. Draper became a charter member, establishing a relationship with the agency that evolved over the years and continues today.

After the initial TFG demonstrations, the gyro performance improvements required for military applications stalled for several years, until Draper identified plasma etching as a solution to limitations associated with the silicon etch technology used to create MEMS structures.

Draper was the first U.S. laboratory to demonstrate the revolutionary deep reactive ion etch (DRIE) process, which allowed us to fabricate thicker parts and high-aspect ratio devices—greatly improving TFG performance and expanding other MEMS-based applications.

DARPA took notice of Draper's breakthrough fabrication capability and funded the completion of efforts to refine equipment for the DRIE process. At the end of this project, DARPA acquired several equipment sets for major research universities, which was instrumental in establishing this new industry standard process across the MEMS community.

THE COMMERCIAL CONNECTION

The development of MEMS devices for commercial applications coincided with post-Cold War budget reductions, and a new focus on dual-use commercial technologies spread across the DOD community. Draper licensing agreements with Rockwell International were consummated in 1993 to bring our microelectronics technologies to market for both military and automotive applications. On signing the licensing agreement, Draper President Ralph Jacobson remarked, "This alliance will bring one of our most significant recent technological advancements directly into commercial markets, thereby benefitting both American workers and consumers."

Initial products targeted automotive applications, and the Draper TFG became the world's first silicon gyro used to demonstrate yaw skid control, a feature now found in almost every automobile. During the wave of corporate mergers among DOD contractors in the 1990s, the license was transferred to Honeywell, which continues to build inertial components and guidance systems based on Draper technology as part of its commercially available product line.

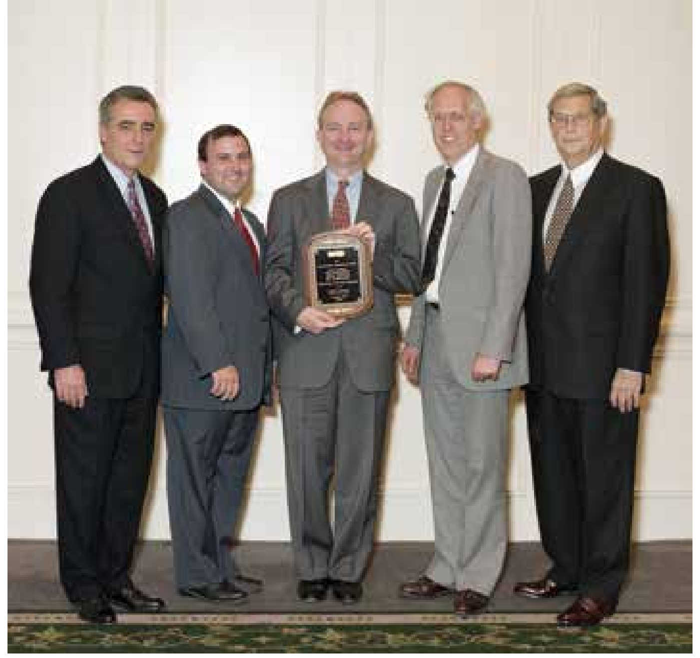
At the time of its initial licensing, the TFG was the highest performing gyro technology available, and its successors remain among the leading technologies used in civil and commercial space applications, as well as commercially manufactured guided munitions.

PRECISION WEAPONS

Initial DOD interest in Draper's microelectronics capabilities focused on high g applications for gun-launched guided munitions, adding an active guidance and control system to previously unguided projectiles. With precision guidance, the military could improve targeting, reduce collateral damage, and potentially reduce logistics costs by an order of magnitude.

Draper developed a MEMS-based inertial navigation system (INS) package that survives high-g loads generated during launch and accurately guides shells to the target. To test the sensors and associated electronics packages, Draper acquired a 100,000-g centrifuge from the Department of Energy and later progressed to drop testing, air guns, and artillery rounds—and even test-firing through concrete walls.

Draper achieved the first successful demonstration of a gun-launched MEMS-based INS/GPS system in 1995 under the Naval Surface Warfare Center's Extended-Range Guided Munitions (ERGM) program. This INS/GPS system consisted of an avionics package containing a MEMS inertial system, with Draper's TFG gyros and pendulous accelerometers, integrated with a Rockwell-Collins military code GPS receiver and flight processor mounted in a 5-in test projectile. The sensors and their discrete electronics were packaged using thin-film hybrid technology in metal housings. Under flight test, the system was subjected to 6,000-g launch forces.



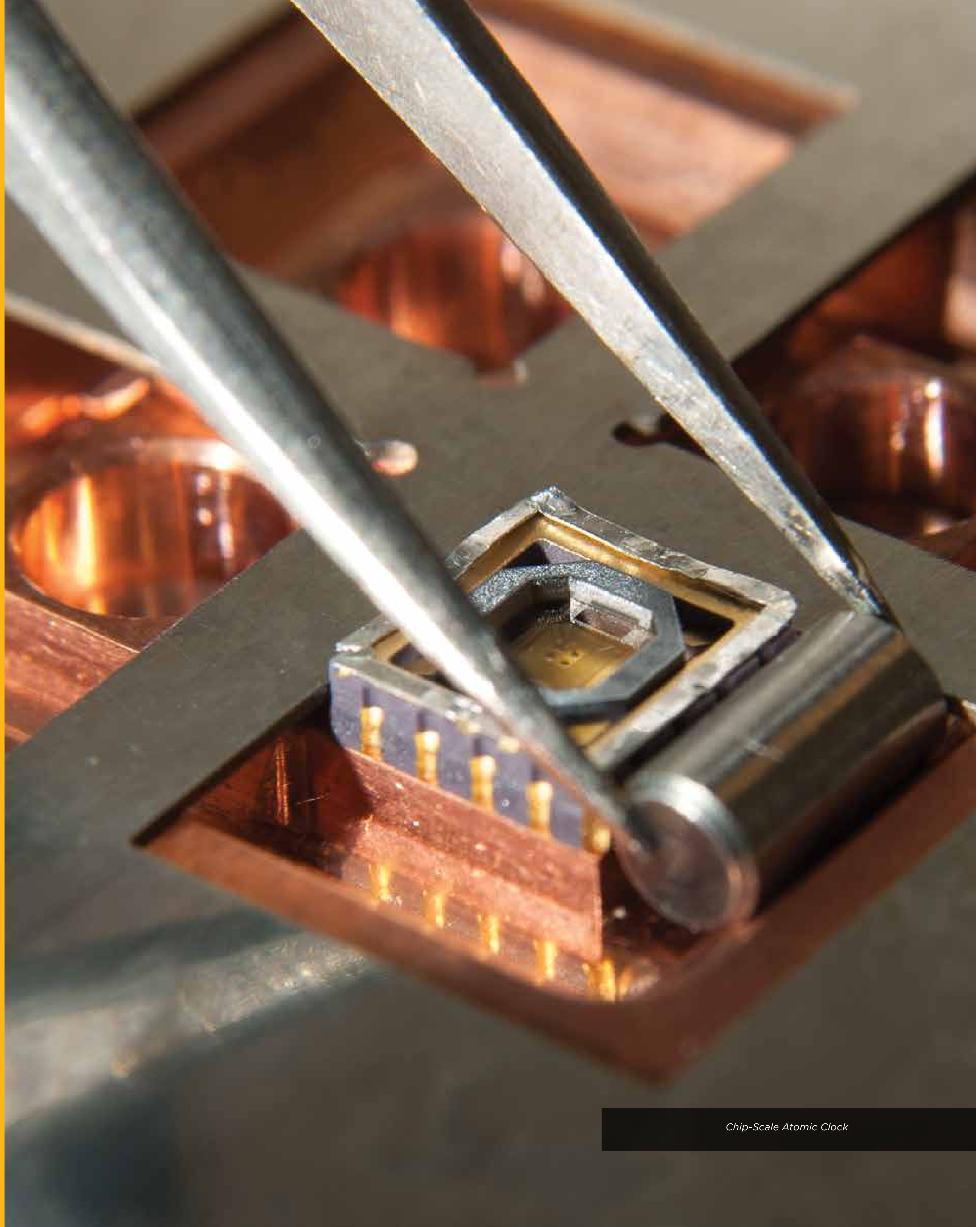
Draper President Vince Vitto (left) and Chairman Bob Hermann (right) presented the 1997 Draper Distinguished Performance Award to (from left) Tony Kourepenis, John Dowdle, and Tom Thorvaldsen for contributions to the ERGM System Integration.

Under a subsequent program with the Office of Naval Research, Draper engineers further miniaturized the system using automotive-grade application-specific integrated circuit (ASIC) electronics and g-hardened multichip modules (MCMs)—reducing the size of the INS/GPS by an order of magnitude. After three successful flight tests at the Yuma Proving Ground, this design became the prototype for the Navy's ERGM and the Army's Excalibur programs. Raytheon's Excalibur projectile initially deployed in Iraq in 2007.

The next step was to develop more affordable IMU and INS/GPS products that could be used as common GNC components across multiple missile and gun-launched munitions programs. Funded by joint Army Science and Technology and Air Force Manufacturing Technology Offices, the Common Guidance Inertial Measurement Unit (CGIMU) and Deeply Integrated Guidance Navigation Unit (DIGNU) programs both produced designs. Draper collaborated with Honeywell to transition the technology into production programs, and the TFG has since been used in numerous DOD weapon systems—including Excalibur, Small Diameter Bomb, Hellfire, and Mid-Range Munition.

As DOD continued its efforts to bring precision guidance to smaller weapons, Draper achieved even greater advancements in miniaturization. Our real-time guidance technology was incorporated into DARPA's EXACTO program, which sought to revolutionize rifle accuracy and range by developing the first ever small-caliber bullet that could compensate for wind, weather, target movement, and other factors. In its first live-fire test in 2014, EXACTO successfully maneuvered in flight, hitting a target offset from where the sniper rifle was aimed.

Extended-range guided munition



Chip-Scale Atomic Clock

DOD TIMING APPLICATIONS

Draper's work in microelectronic timing applications followed a path similar to that of our miniaturized inertial guidance systems: DARPA provided the seed funding that enabled major technological breakthroughs, Draper advanced the technology and eventually licensed it for commercial use.

In early 2002, Draper launched a project funded by DARPA to revolutionize high-accuracy, low-power timing devices. The goal was to develop portable timing devices with 100 times better performance than similar low-power oscillators, replicating the performance of systems that were hundreds of times larger and more power hungry. This aggressive program started as a collaboration among Draper Laboratory, Symmetricom, and Sandia National Laboratory.

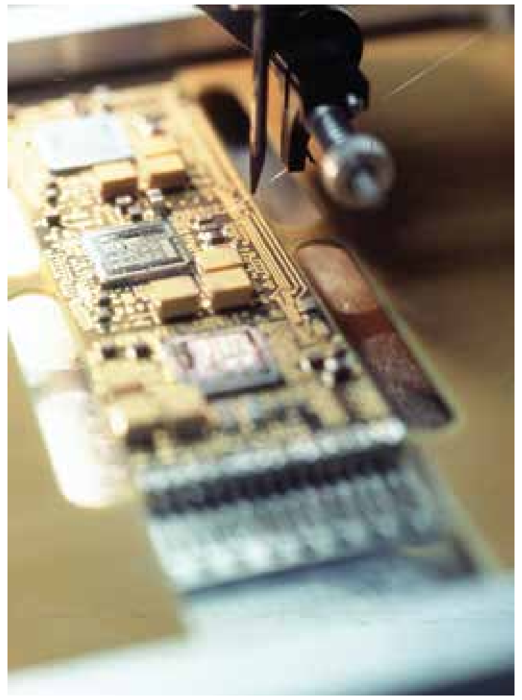
The team's ultimate success was driven by two critical innovations. The low-power optical system was enabled by Sandia's miniature high-modulation bandwidth Vertical Cavity Surface-Emitting Lasers (VCSELs). Draper's team invented a new, enabling MEMS technology—an ultra-low power thermal stabilization platform.

The full atomic clock required only 100 mW of power and occupied 15 cm^3. This technology was transitioned to our commercial partner and made available as a commercial product in 2011 and is now commonly used in satellites.

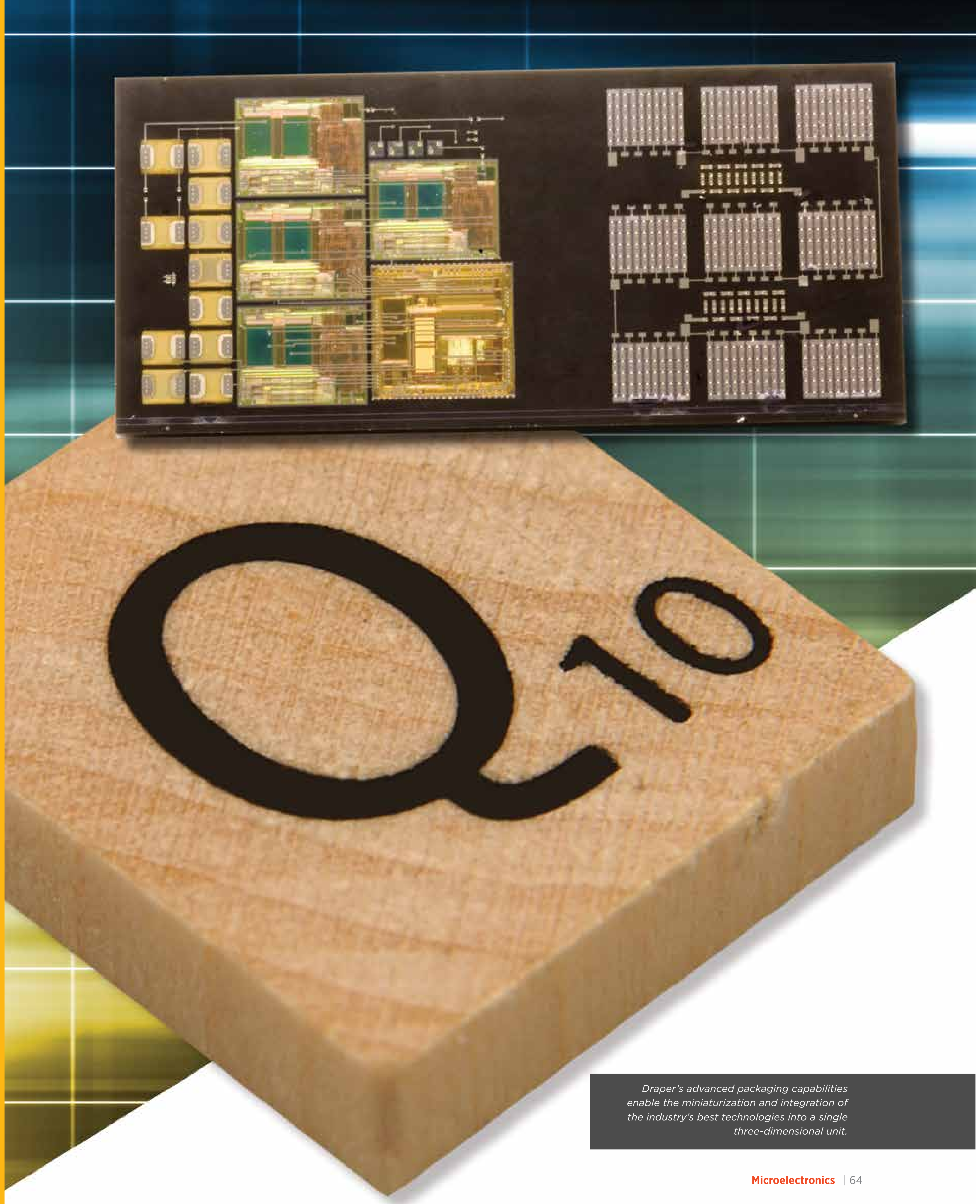
By 2014, Draper had once again revolutionized atomic timekeeping by solving for the known drift of commercial chip-sized atomic clocks. By applying a technique used in nuclear magnetic resonance spectroscopy, our engineers were able to reduce the size and cost and improve the stability of laser-based atomic clocks.

Under DARPA's Atomic Clock with Enhanced Stability (ACES) program, Draper joined a team of researchers to develop an atomic clock with 1000x improvement in temperature control, aging, and retrace. Successfully demonstrated in 2019, the clock consisted of photonic integrated chips, a 3-mm vapor cell that housed rubidium atoms, and a laser that tracked the atoms' oscillations. By microfabricating all the key components, Draper was able to create a potential path to integrate the electronics and optics for mass production and commercialization.

Draper engineers continue to pursue advancements in microelectronics to drive the next generation of atomic clocks, investing IRAD funding to explore promising but as-yet elusive quantum and cold-atom technologies—bringing today's state of the art into tomorrow's functional systems.



Multichip module



Draper's advanced packaging capabilities enable the miniaturization and integration of the industry's best technologies into a single three-dimensional unit.

ADVANCED PACKAGING

In parallel with MEMS development, Draper made significant advancements in miniature electronics packaging technologies. By combining MEMS devices with miniature electronics, Draper was able to build complete miniature systems, opening up many new applications for the devices.

In the earlier years, Draper engineers made numerous advancements in interconnect density—as well as power, weight, and volume—to meet the vision for compact and robust components, sensors, and systems.

In the early 1990s, Draper's high-density electronics packaging efforts were led by Paul Van Broekhoven, and we soon began to build MCMs. The basic MCM fabrication process consisted of recovering bare die from multiple integrated circuits (ICs), thinning the die, and then repackaging them with the interconnects built on top. By eliminating the IC packages and the space between them, our engineers reduced the volume significantly relative to high-density circuit board implementations. With this technology as a key enabler, Draper was able to significantly expand our offerings to the intelligence community, which needed small, low-power sensors for intelligence, surveillance, and reconnaissance applications.

In 2005, driven by an increasing demand for even smaller electronic devices and more efficient production methods, Draper undertook a challenge to develop an entire system—battery, antenna, processor, sensors, and other components—that would fit into a package the size of a Scrabble® tile. To meet this challenge, we established our own Vanishingly Small Systems (VSS) initiative aimed at developing increasingly small, lower-power devices that provided enhanced functionality.

Leveraging both commercial semiconductor and MEMS processes, Draper created a new wafer-scale injection molding process to stack and electrically interconnect circuits called integrated Ultra-High Density (iUHD) packaging. Our 3D stacked iUHD system was designed to resemble chip-scale packages and to be both customizable and compatible with multiple materials and substrates. The system components are buried in the substrate and use through-substrate vias to connect to both sides of the substrate. The iUHD process initially resulted in packages with less volume than those produced by the previous MCM process. Since then, we have developed the iUHD packaging technology in stacked modules with redistribution layers, exceeding the capabilities of the most advanced commercial MCMs.

In response to increasing demand by key sponsors for larger quantities of our VSS applications, in 2008 Draper opened a microsystems fabrication facility. Four years later, as the complexity of the iUHD systems continued to increase, we consolidated our MEMS and VSS research facilities into a single state-of-the-art facility. In 2012, Draper expanded our capabilities to support advanced packaging beyond the iUHD.

Our high-trust relationship with the federal government continues. Leveraging technology maturation contracts, Draper was selected to manufacture, qualify, and deliver a hardware component designed to protect critical technology from compromise and exploitation under a DOD program of record. Recently, we shipped the first production components and, drawing on Draper's high levels of technology and manufacturing readiness demonstrated for the product, we will support multiple concurrent contracts for production deliveries years into the future.

ENGINEERING FOR HOSTILE ENVIRONMENTS

Beginning with our work on ballistic missile guidance in the 1950s, Draper has led the nation—and the world—in ultimate safety electronics. We have long been the U.S. government's source for strategic systems that must remain operational under extreme or hostile conditions.

Draper has an unparalleled reputation for designing and developing radiation-hardened (rad-hard) microelectronics—from precision analog instrumentation to high-throughput processors—that achieve the highest levels of performance. As of 2023, we are the only laboratory to successfully deploy a rad-hard system in the 21st century.

Our experience extends beyond the natural radiation environment of space to the prompt-dose radiation and extreme thermomechanical effects that occur during natural and human-made nuclear events and explosions.

Beginning in the early 2000s, Draper led efforts to upgrade the guidance system for the U.S. Navy's TRIDENT II missile. As part of the MARK 6 MOD 1 program, we provided computers, gyroscopes, accelerometers, ASICs, and other electronics capable of withstanding conditions during launch and boost phases. Our engineers designed all aspects of the guidance to detect, absorb, and recover from high-input rates of radiation while maintaining a high degree of precision—retrofitting the Navy's linchpin nuclear defense system for continued service through 2042.

When NASA sought to develop a probe capable of orbiting the Sun, Draper developed a custom radiation-hardened electronics system to ensure the probe's science instrumentation could operate under the extreme conditions within the corona. Launched in 2018, the Parker Solar Probe will come closest to the Sun and achieve the highest velocity of any human-made object. For our part in this monumental achievement, Draper was recognized as part of the core team with the NASA Silver Achievement Medal in 2019.

By the advent of the 21st century, the market for personal electronics had driven electronics manufacturing overseas, creating a critical gap in the government's ability to ensure access to microelectronics that were free from defects or malware for defense and security systems. Congress acknowledged this concern in its 2017 National Defense Authorization Act and again in 2022 with the signing of the CHIPS and Science Act.

To address the U.S. government's focus on trusted and assured microelectronics, Draper applied our expertise to the problem of cyber security, physical security, and rad-hard systems for U.S. government use. We designed systems with built-in safeguards against reverse engineering and radiation effects, developing solutions that range from commercial electronics applications through highly secure customized components that only Draper can build. In 2018, the Defense Production Act Title III Office selected Draper to deploy one of our packaging technologies to help expand domestic supplier production of 3D, ultra-high-density microelectronics modules for use in mission critical applications. DOD extended funding for this work in 2021.

Today, Draper is leading the charge across government and industry to adapt state-of-the-art commercial technology for use in hostile environments—which demand high fault tolerance and operational safeguards against everything from radiation, heat, and shock, to radio frequency and cyber attacks. Draper is one of the only R&D firms capable of engineering these next-generation strategic systems, leveraging foundries and infrastructure with highly specialized fabrication and assembly to deliver high-throughput national security systems at lower costs.

Often called in to consult on efforts led by defense industrial base and commercial contractors, Draper has earned a reputation as experts in design, safety, reliability, and manufacturability.

Waffle-pack of Radiation-hardened modules

Draper is assisting the U.S. Space Force with test planning for the next-generation GPS IIIF satellite (rendering shown).

GPS AND ASSURED POSITIONING, NAVIGATION, AND TIMING

Draper has played an integral role in the development of global positioning system (GPS) technology since its earliest concepts and foundational technologies. Even then, our engineers recognized that GPS alone could not provide reliable positioning, navigation, and timing (PNT) in harsh or contested environments. Drawing on our strengths in miniaturizing instruments for military GNC systems, some of our earliest efforts sought to integrate inertial navigation systems (INS) with GPS. Decades later, this work proved to be highly prescient as the Department of Defense shifted from a focus on a pure GPS solution to one that combines GPS with alternative sensor architecture—such as INS—for future military navigation systems.

Draper's work on GPS technology started in the late 1970s, when a team of Draper engineers began exploring the potential for inertial measurement technology to augment GPS receivers. Draper's Duncan Cox used extended range code tracking for improving the acquisition of NAVSTAR GPS signals in the presence of jamming and demonstrated a pre-correlation digital P-code GPS receiver. In collaboration with Richard Greenspan and Charles C. Counselman III, the Draper team also demonstrated pioneering techniques for processing GPS carrier phase signals to provide measurements of short baselines with millimeter accuracies. At the invitation of Bradford Parkinson, lead architect for the Air Force NAVSTAR GPS program, Greenspan authored a chapter in the foundational textbook on GPS technology, published in 1996.

The early 1990s also marked the first of Draper's contracts with the GPS Directorate* to support GPS infrastructure. Our initial contributions included an architectural evolution plan (AEP) study that informed the design of the master control station that commands GPS satellites today.

Beginning in 1995, our engineers began designing and building a new test capability at Cape Canaveral, Florida: the GPS Telecommunicators Simulator Test Station (TSTS). The TSTS is a shirtsleeve environment with several "iron bird" satellite simulators in electromagnetic-shielded rooms, as well as remote site equipment simulators that can be commanded from test sites in Colorado Springs, Denver, and Vandenburg SFB. In continuous service for more than 25 years, the TSTS enables the GPS Directorate and its contractors to perform end-to-end system requirement verification and testing of both satellite and ground system technologies—ensuring every new hardware or software technology is fully validated before becoming operational.

Draper designed and built the GPS Telecommunications Simulator Test Station at Cape Canaveral Space Force Station, Fla. The facility supports end-to-end system requirement verification and testing of satellites and ground system technologies.

In the late 1990s, the federal government sought to take advantage of advances in computer technology and timing devices to improve the performance of its satellites, to expand GPS support for civilian aircraft and rescue missions, and to improve GPS for the U.S. military and allied nations. Dubbed GPS Modernization, this effort added several new military and civilian signals. Draper joined the program in 2004 and, in collaboration with the MITRE Corp and SRI International, began ground testing of the first modernized satellite, which launched the following year.

Today, the Draper/MITRE/SRI team continues to provide testing and validation services in support of GPS modernization—including the military code (M-code). M-code is a stronger, encrypted GPS signal designed to meet military needs for PNT. Our team tests modernized satellites both pre- and post-launch, measures Inter-Bias Differentials to calculate the Inter-Signal Corrections transmitted by every GPS satellite, conducts monthly satellite health checks, tests new software prior to and after implementation in on-orbit satellites, verifies that new capabilities do not interfere with legacy GPS signals, participates in formal Integrated System Tests as directed by the U.S. Space Force, and evaluates anomalous GPS satellite performance as needed. Our most recent work also includes assisting the Space Force with test planning for the next-generation GPS IIIF satellite, which will provide an improved anti-jamming capability to ensure U.S. and allied forces cannot be denied access to GPS in hostile environments.

Together, these testing activities help ensure that GPS is always available to serve the agencies, missions, systems, and individuals who rely on geolocation and timing every day.

Draper has also developed several technologies to replace GPS navigation in environments where the signal is denied or even spoofed. While inertial navigation can successfully augment GPS, INS alone is subject to drift, losing accuracy over time. Whether on Earth or in space, crewed and autonomous systems need assured PNT to complete their missions. To address this gap, Draper developed numerous advancements to augment inertial systems with celestial or vision-aided geolocation.

One example is our Skymark system. Patented in 2019, Skymark combines a telescope, a database of celestial objects, and a powerful processor to enable triangulation of resident space objects against the star background. The result: a ruggedized package suitable for air, space, and sea-level applications. The Skymark system was successfully demonstrated in 2020.

LOOKING AHEAD

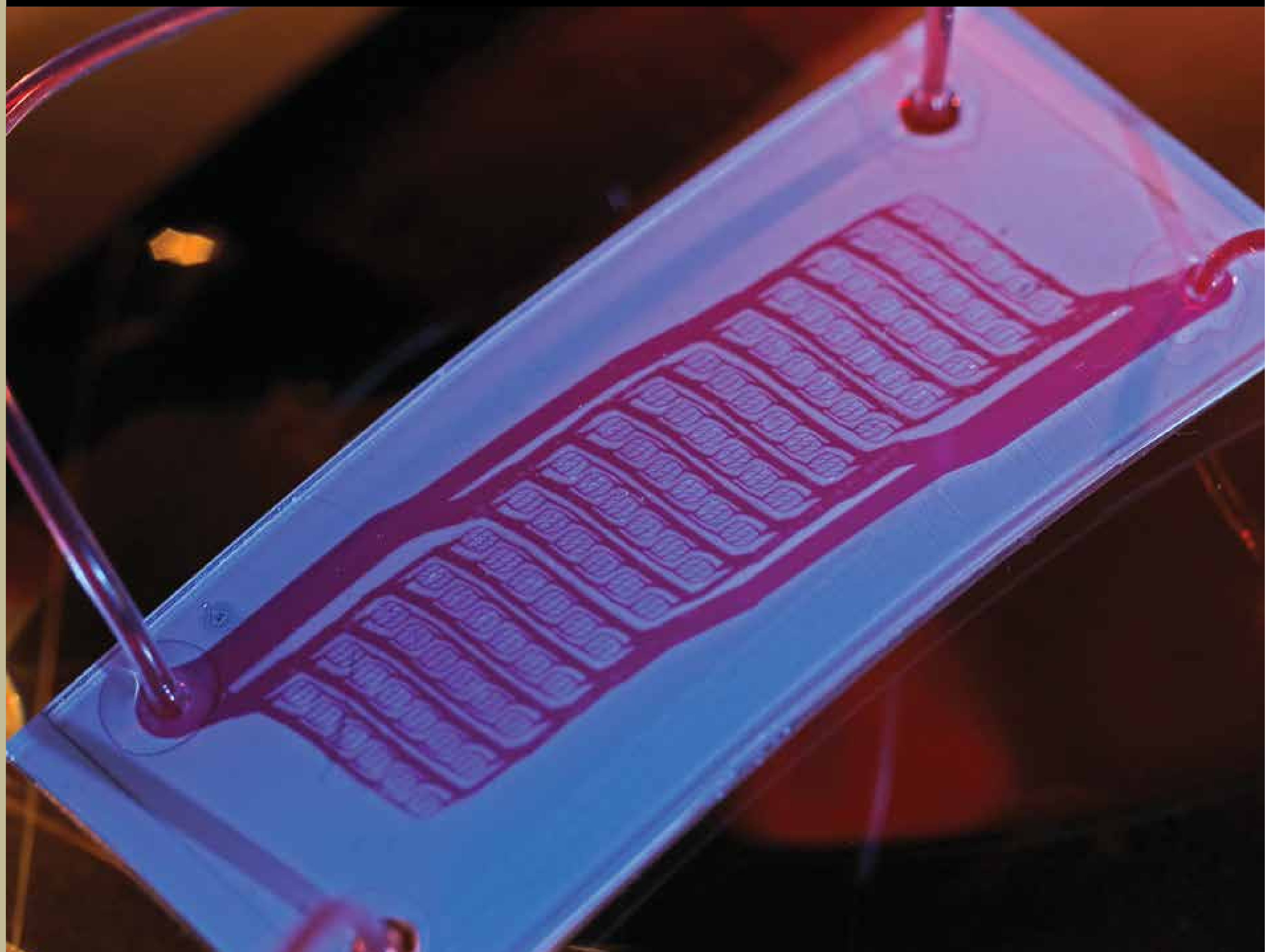
Draper's innovative approach to design, development, and packaging has made it a leader in microelectronics for military, space, and national security missions.

As Draper joins with U.S. industry to bolster our nation's leadership in semiconductor R&D as part of the ME Commons created by the 2022 CHIPS and Science Act, we bring to bear nearly four decades of experience in the field and our unwavering commitment to supporting America and her allies and defending freedom throughout the world.

At the same time, we recognize that fully securing our nation's interests will demand a higher degree of protection in consumer electronics as well—automotive vehicles, banking systems, the Internet of Things, and more. In the decade ahead, we anticipate significant opportunities to transition Draper innovations into commercial production.

* Originally known as the GPS Joint Program Office and later the GPS Wing, in 2016 the GPS Directorate shifted from oversight under a committee chaired by DOD and the Department of Transportation to the U.S. Space Force.

(CHAPTER 8)



Draper reported our work on the first artificial blood vessel network using MEMS technology at the 2001 MicroTAS conference.

Biotechnology Engineering for Health and National Security

EVOLVING FIRST-OF-KIND TECHNOLOGIES INTO FUNCTIONAL PRODUCTS AND SYSTEMS

Biomedicine became a focus at Draper as early as 1972, when Doc Draper created a mission to help prevent disease and disability and to increase the access to affordable, high-quality healthcare. Early projects focused on applying our technical advancements in MEMS and microelectronics to challenges in diagnostics and drug delivery. Over the years, our mission and partners expanded, and Draper developed new capabilities to support these efforts, including microfluidics and life sciences.

Building on our foundational technologies, Draper engineered increasingly sophisticated medical applications and broadened the focus of our work to address problems in biodefense and warfighter support. Today, Draper is one of few companies with the expertise, facilities, and instrumentation necessary to perform a wide range work spanning high-containment, classified, and clinical spaces for our commercial and government partners.

Dr. Joseph Vacanti of Massachusetts General Hospital examines a model of an organ vascular system with Draper's Jeff Borenstein. MGH and Draper collaborated on projects through the Center for Innovative Minimally Invasive Therapy, a consortium the two organizations cofounded with Brigham and Women's Hospital and MIT.

EXPANDING FROM BIOMEDICINE TO BIOTECHNOLOGY R&D

Draper's first decade of biomedical solutions included technologies that digitized electrocardiogram signals to screen for abnormal results, a laboratory information system for Boston Medical Laboratory, an automated microscope for Tufts New England Medical Center, hardware and software for ultrasonically and noninvasively mapping blood flow, and a portable and inexpensive bedside cardiovascular disease monitor.

In the 1980s, Draper patented a device that used a light-emitting diode array to magnify and display graphical material for the visually impaired. Clinicians sought our assistance to develop sensors that could identify defects in artificial heart valves post-implantation, and we designed the electronic control and monitoring system for one of the first implantable ventricular assist systems.

Our collaborations with Boston-area clinicians expanded in the 1990s, transforming Draper's biomedical work into a formalized business program. We joined the Neural Prosthesis Research Center (NPRC), a consortium funded by the Keck Foundation. In partnership with MIT and the Massachusetts Eye and Ear Infirmary (MEEI), Draper made significant advances under the NPRC in both cochlear and retinal implants, and laryngeal and vestibular prostheses. In 1998, Draper joined Massachusetts General Hospital, Brigham and Women's Hospital, and MIT as a founding member of the Center for Integration of Medicine and Innovative Technology (CIMIT), a consortium funded by the Army Medical Research and Materiel Command.

MODELING ORGANS AND ORGAN SYSTEMS

Starting in the late 1990s, Draper was the first to use MEMS for tissue engineering and early organ-on-chip applications, resulting in more than 15 patents. Using MEMS techniques our engineers created precise architectures that mimic blood vessel networks, providing scaffolds on which cells can grow. These efforts initially were funded by CIMIT and led by Jeff Borenstein in partnership with Joseph Vacanti at Massachusetts General Hospital and Robert Langer at MIT. In 2002, Draper was the first institution to successfully demonstrate mammalian cell culture in a microfluidic device.

These initial efforts focused on growing cells outside the body to harness biological processes and outputs for therapeutic use. By the early 2000s, Draper was combining computational fluid mechanical analysis and designs with microfabrication techniques adapted for biologically compatible materials and 3D assembly techniques. Our engineers pioneered the field of microfluidic platforms for regenerative medicine, demonstrating numerous first-of-a-kind prototype organ assist and organ replacement devices, including microvascular networks for vital organs, renal dialyzer cartridges, and liver assist devices.

In 2004, Draper began applying microfluidic cell culture systems to drug development, through a collaboration with Massachusetts General Hospital and Pfizer. This program led to the development of microfluidic liver models for fibrosis research and microfluidic vascular models for safety applications such as drug-induced vascular injury. In 2011, Draper began working with DARPA and the University of Massachusetts Medical School to develop lung-on-a-chip devices for influenza research. The following year, we joined a multidisciplinary research team to undertake a project dubbed Barrier-Immune-Organ: MIcrophysiology, Microenvironment Engineered TIssue Construct Systems (BIO-MIMETICS). Funded by DARPA, BIO-MIMETICS sought to develop microscale technology that realistically mimicked human organs in a laboratory environment for novel drug and vaccine testing. Such models held enormous promise to accelerate drug discovery and improve outcomes by identifying potential side effects such as liver toxicity, a common cause for the discontinuation of clinical trials on a drug.

Under the project, Draper's single-organ prototypes—including complex systems such as the lung and liver—were linked together to create platforms that modeled the interactions between multiple organs. This research was published in *Lab on a Chip* in 2016. In 2017, through an NIH-funded collaboration with Northwestern University Medical School, Draper co-authored a paper in Nature Communications, heralding our breakthrough success in linking five organs toward modeling the female reproductive tract using what had become known as the Human Organ System platform.

PREDICT96 is a multiplexed, single-organ system that models and captures data on how compounds and functioning human tissue models of organs interact. This high-throughput technology enables rapid parallel testing of dozens of compounds.

This system ran in uninterrupted operation for over 100 days at Northwestern, the longest duration multi-organ system ever demonstrated. The device enabled the recapitulation of all organ-level functions in a stable and precise manner and successfully triggered ovulation. By engineering an environment that mimics actual function in the female body, the Draper device allowed researchers to safely study the reproductive toxicity of new drugs and eventually will advance treatments for fibroids, endometriosis, infertility, and certain cancers.

In 2016, Draper began a major organ-on-chip collaboration with Pfizer, focusing on many of the most important and challenging disease areas in need of new pharmaceutical R&D tools. During this time, Draper was developing the first high-throughput instrumented organ-on-chip platform, dubbed PREDICT96. This engineered platform featured 192 microfluidic pumps to control flow precisely, built-in electrical sensors for real-time collection of in vitro data, and a 96-well design for easy integration with commercial lab automation and screening tools. Over subsequent years, PREDICT96 was further developed in partnership with several other commercial companies such as Bristol Myers Squibb and Colgate Palmolive, and government agencies—including DARPA under the PREPARE program. In 2021, the Biomedical Advanced Research and Development Authority (BARDA) funded Draper to adapt PREDICT96 to study SARS-CoV-2 infection, and we became the first research lab to successfully infect a humanized lung model within our BSL-3 containment facility.

Today, Draper has developed models for all major organ systems, and with BARDA support we are developing a model of the human lung that integrates immune cells. Our research continues to keep pace with scientific understanding of human systems, extending to the human microbiome to model the symbiotic relationships that play a critical role in physical and mental health.

MEDICAL DEVICES AND DIAGNOSTICS

Draper's expertise in 3D scaffolding, tissue engineering, and microfluidics has supported numerous innovative medical devices and diagnostic advances.

For example, in 2008 we launched an internally funded effort to develop a microfluidic blood oxygenator—dubbed BLOx—with the potential to transform life-saving treatment for people suffering respiratory failure. This technology was further advanced in collaboration with the National Institutes of Health, a leading medical device company, and a multinational healthcare company. Incorporated into a MEMS-based extracorporeal membrane oxygenation (ECMO) system, BLOx is a major advancement that could enable portable ECMO machines. Major commercial collaborations on microfluidic kidney assist devices were also advancing during that time, aimed at revolutionizing dialysis treatment for hundreds of thousands of patients suffering end stage renal failure.

Our ECMO device has a much higher oxygen transfer efficiency than competitor microfluidic devices or commercial hollow fiber oxygenators, is far less prone to clotting, and has demonstrated the highest blood flow rate of any microfluidic device ever reported. With funding from the U.S. Army Medical Research Acquisition Activity in 2022, the ECMO device entered a large preclinical study, bringing it one step closer to commercial or military use.

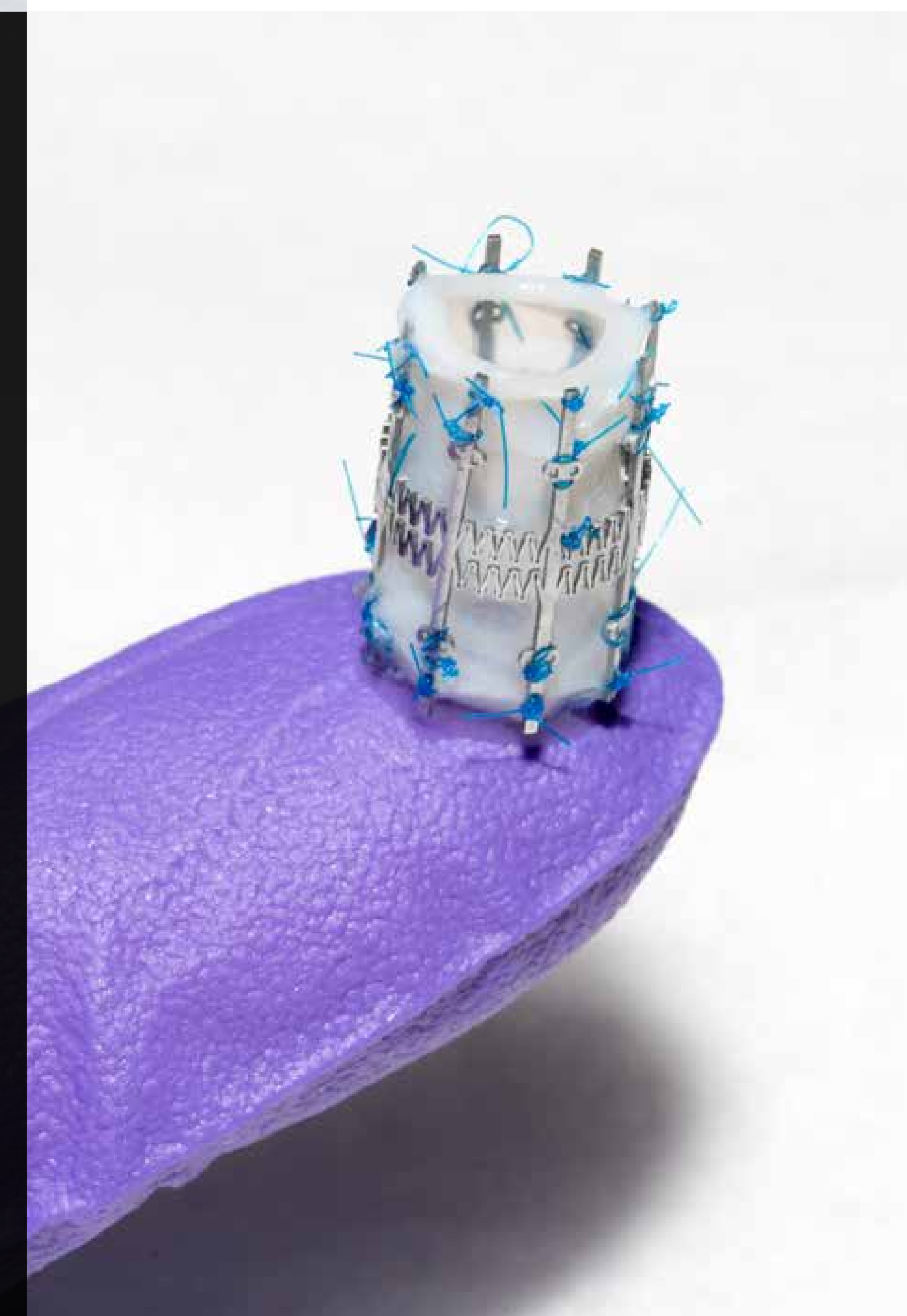
In 2017, Draper committed internal funding to undertake development of a pediatric heart valve prosthetic—a critical unmet need that forces infants with congenital heart defects to undergo as many as five surgeries to replace values as they grow. By 2021, our Low-force Expanding/Adaptable Pediatric (LEAP) Valve—the first heart valve that can grow with the patient—had earned recognition from the both the Children's National Health System and the American Society for Artificial Internal Organs. With funding from the U.S. Army Medical Research Acquisition Activity, Draper's device entered preclinical studies in 2022 at two children's hospitals, supporting further development as an investigational device under the FDA's Humanitarian Device Exemption pathway.

Draper also leveraged the microfluidic capability used in BLOx to address kidney dialysis. Currently, blood is "cleaned" through what is called a counter current concentration gradient. This approach works well for small molecules like urea, but larger molecules like beta globulin require more time and force to pass out of the blood. To help prevent poor health outcomes associated with the buildup of these larger molecules, Draper's microfluidic approach "washes" the blood by flowing in fresh dialysate while simultaneously drawing out impurities. This approach achieves similar clearance of small molecules and significantly increases clearance of larger ones—by effectively mimicking the function of a human kidney.

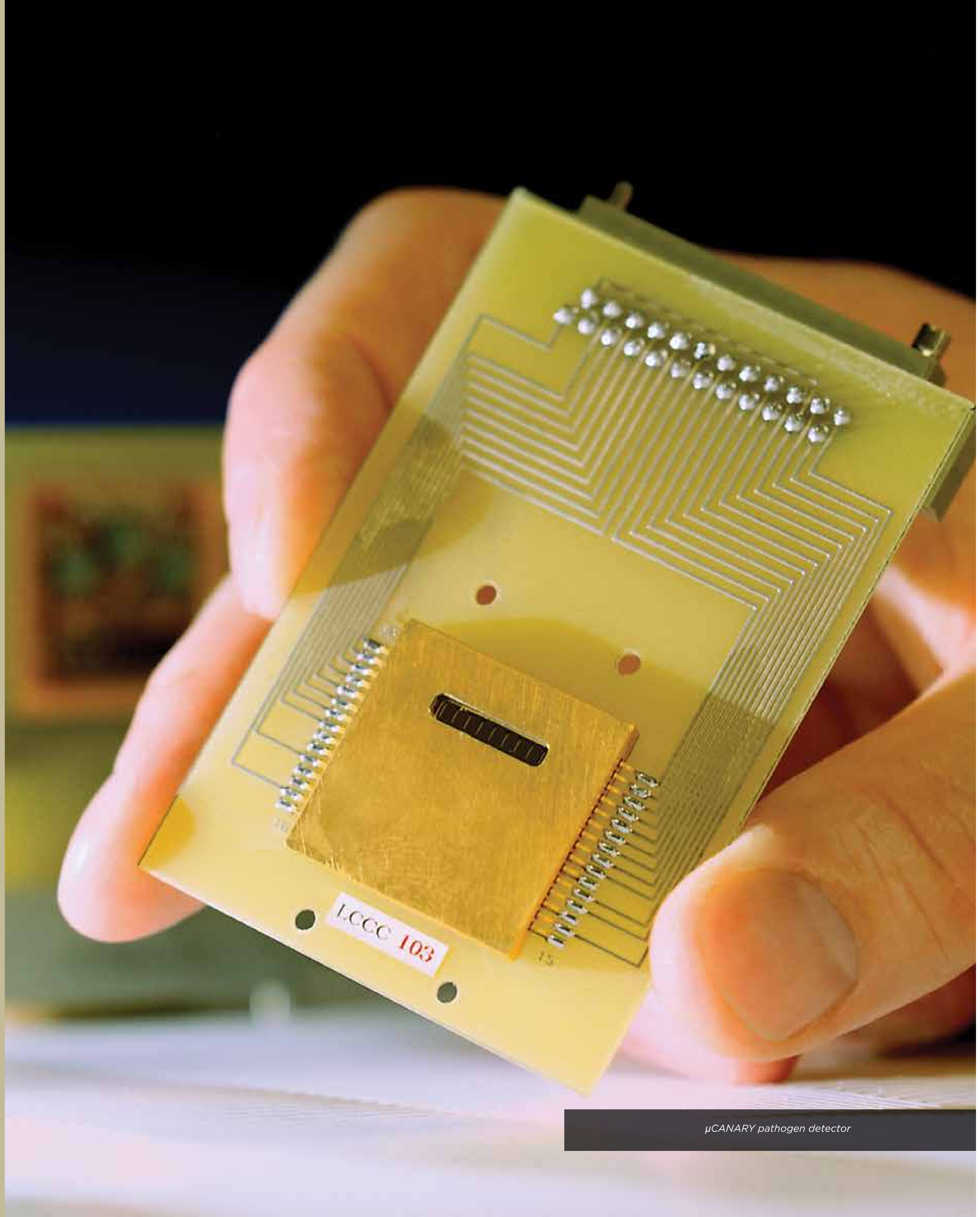
Draper's work on the differential ion mobility spectrometer (DMS) also began in 1997. DMS is a micromachined device that detects atmospheric pressure and gas phase in the parts-per-trillion range. Conceptually similar to a quadruple mass spectrometer, the DMS measures ion mobility rather than ion mass, acting as an electrically tunable ion filter. Later, in collaboration with Brigham and Women's Hospital, Draper adapted DMS to develop a breath-based test for invasive aspergillosis, a debilitating fungal infection of the lung. In 2022, Vox Biomedical licensed DMS for use in the first-ever breathalyzer device to detect recent use of marijuana and opioids—closing a critical gap for law enforcement, workplace safety testing, and emergency medical services. Today, our engineers are working to recapitulate the system to accelerate testing and production of cell therapies.

A single layer of Draper's microfluidic oxygenator design called BLOx2-R1. Our design achieved a blood flow of 100 mL/minute, the highest rate ever reported in a microfluidic device..

To measure volatile organic compounds in air samples, Draper developed a sensor system incorporating differential ion mobility spectrometry (DMS) technology and programmable compact gas chromatography. Draper's microAnalyzer™ detects trace vapors in concentrations as low as a few parts per trillion.



Draper's Low-force Expanding/Adaptable Pediatric (LEAP) Valve is the first heart valve that can non-invasively adapt to growth with the patient. The device entered preclinical studies in 2022 in collaboration with Boston Children's Hospital and Seattle Children's Hospital.



µCANARY pathogen detector

BIODEFENSE

Much like our biomedical applications, Draper's contributions to biodefense built on our foundational capabilities in MEMS, resulting in novel, highly sensitive sensors for detecting chemicals and biological pathogens.

For example, in 1997 Draper developed a microfluidic, resonance-based technology for rapid detection of microbial pathogens. The micro-Chemical Analysis Array (µCANARY) was developed in response to a DARPA call for chem/bio detectors and was licensed to Bioscale, Inc. in 2003 for use in products for water purity detection and food safety applications.

Under various licenses, our DMS sensor technology has enabled devices used to detect chemical warfare agents, toxic industrial chemicals, explosives, and bio-threats. A version of the DMS detection platform—dubbed the microAnalyzer™—is currently deployed on the International Space Station as an air quality monitoring system. In 2015, the system proved invaluable, successfully confirming that the cause of a reported ammonia leak in the US module was a faulty pressure sensor. Because the Draper technology can be operated remotely, the crew was able to isolate safely in the Russian module during the incident.

In 2021, Draper was awarded a DARPA contract under its "Detect It with Gene Editing Technologies" (DIGET) program to help develop a portable device capable of screening clinical or environmental samples for up to 1,000 nucleic acid targets—with a program goal of sample to results in 15 minutes. With Draper's contributions, the MMD aims to alter the concept of operations for biosurveillance by increasing throughput, sensitivity, and usability to levels unmatched by existing technologies—identifying species, strain, antimicrobial resistance, and other genetically encoded characteristics in a single test run.

As Draper continues our biosecurity R&D, we continue to look for opportunities to improve protection and detection. Ongoing explorations include detection of microbiome signatures to better understand infection resilience as well as treatment, as well as novel application of our electroporation capabilities to develop antibody assays.

BIOPROCESSING

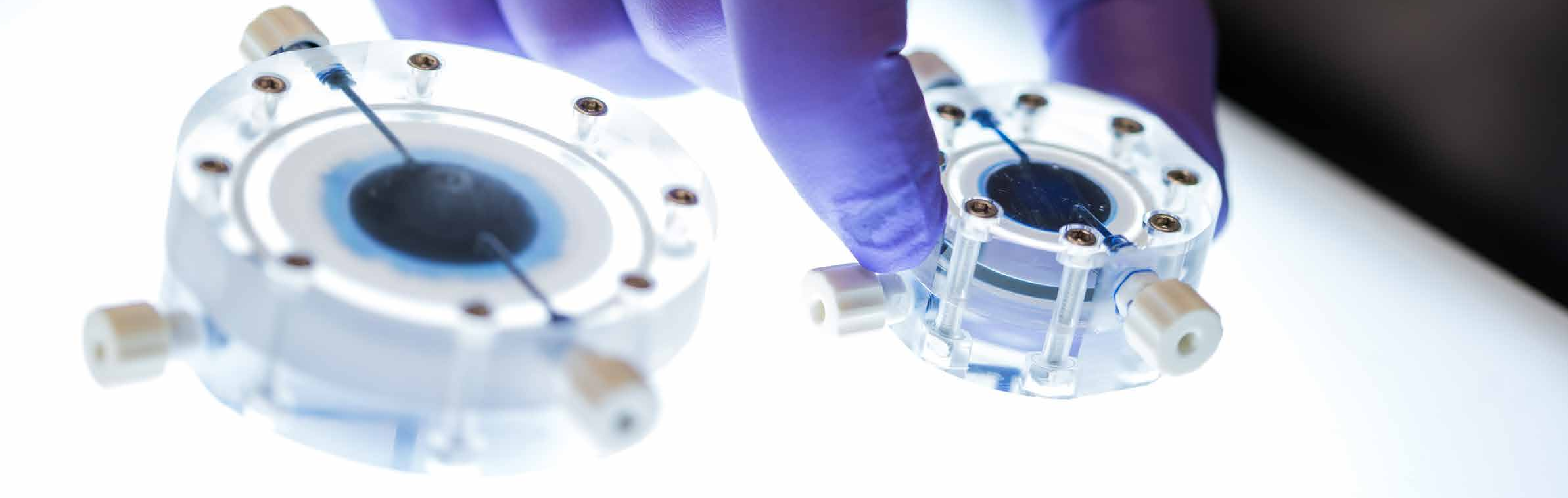
As the use of cell and gene therapies to treat cancer, injury, and degenerative diseases became more common, researchers needed high-throughput discovery tools, and manufacturers sought innovative technologies to accelerate manufacturing processes, reduce cost, and control quality and safety.

In 2016, Draper developed a microfluidic transduction device that enables CAR-T cell therapies to be manufactured with just half the viral vector of previous technologies, dramatically reducing the cost. Designed for easy integration into existing lab automation systems, the system enables novel flow structures to maximize proximity of vectors to patient's cells and thereby efficiently deliver genes. In addition to being first-of-a-kind technology for safer, cheaper cell therapy production, the platform also proved to effectively enhance transduction in human stem cells . Draper initiated the research with internal funding and published the results in 2019.

In pursuit of a nonviral process for genetically modifying cells, in 2016 Draper began developing a high-throughput, continuous-flow microfluidic electroporation system. By controlling the exposure of cells to pulses of electricity, electroporation renders cells temporarily permeable to genetic material. The Draper system offers several key advantages over traditional bulk electroporation. For example, by enabling spatial separation of cells and precise control of the electric currents, the microfluidic geometry helps maximize cell health. By electroporating cells in continuous flow, the system also delivers unprecedented throughput—transfecting up to several billion cells per hour. Together, these capabilities will help enable the next generation of off-the-shelf cellular therapies. Draper published the results of this internally funded R&D effort in 2019 and 2020, and we have since pursued further development in partnership with a major cellular therapy manufacturer, with a goal of deploying systems for clinical testing in 2023.

In 2019, the U.S. Food and Drug Administration (FDA) awarded a contract to Draper to develop another technology to accelerate production of cell therapies. With previous funding from DARPA and NIH, we had already made pioneering advances in microfluidic acoustic cell separation and demonstrated its value for blood sample preparation and purification. Draper's key innovation was the first-ever demonstration of acoustic separation in plastic cartridges, which opened the door to low-cost, disposable clinical devices.

Under the FDA contract, our bioprocessing engineers adapted the system for continuous, label-free purification for both autologous and allogeneic cell therapy production. Draper's system uses



Draper's microfluidic transduction device is designed to enable companies to manufacture T-cell therapies with less of the viral vector required by many current approaches.

ultrasonics to separate and purify cells by tuning or manipulating differences in their size, density, or compressibility. As a result, the system can operate without the need for antibody-based reagents, batch centrifugation, or other process steps that escalate the cost of manufacturing cell therapies. Draper has since developed multiple demonstration units for pre-clinical testing. We have also demonstrated high-throughput processing at clinical scale and achieved complete purification of T cells without addition of costly separation beads.

Building on this work, Draper has partnered with several Fortune 500 pharmaceutical companies to improve the efficiency of their operations. For example, in 2021 we entered into a strategic collaboration with Gilead's Kite Pharma, the first company with multiple approved CAR-T cell therapies, to customize our bioprocessing technologies and enhance development of their pipeline cell therapies. Under this effort, we delivered clinical systems and automations for acoustic cell separation, transduction, electroporation, and buffer exchange. Together, Draper innovations resolve long-standing inefficiencies in the cell therapy production process, which will make these life-saving treatments more affordable for payers and patients.

In 2023, Draper adapted our bioprocessing technologies to support exosome-based therapies, a capability as yet unmatched by any other laboratory. Our engineers are committed to working with industry partners to further develop our modular systems to streamline and improve patient access to emerging therapies of interest.

LOOKING AHEAD

As we scan the horizon, Draper stands ready—as a trusted partner for government, commercial pharma, clinicians, and academia—to tackle the urgent and emergent problems facing our world. We will continue to advance the fields of microfluidics and MEMS to improve medical diagnostics and therapeutic sensors, and we will extend our innovations in electroporation to enable sophisticated antibody screening tools in support of biodefense.

We expect to see growth in our synthetic biology capabilities and to further expand our application areas—including food insecurity and plastic remediation, harnessing biologics for energy production, supporting space missions, and tackling other intractable problems.

As ever, Draper takes the long view, seeking not only to innovate and design first-of-kind biotechnologies, but to turn our engineering and scientific breakthroughs into transformative and functional products and systems.

CHAPTER 9

Doc Draper with Draper Fellow John Stillwell, who later became a U.S. Navy Captain and then Draper Vice President for Strategic Systems

Technical Education and R&D Partnerships in the National Interest

LEARNING BY SOLVING REAL-WORLD PROBLEMS

Technical education is a national imperative and a vital objective of Draper's mission. It has been a constant across our history, having its genesis in Doc Draper's motivation to offer real-world research opportunities for his students. From our origins as a laboratory integrated within MIT's academic structure—and specifically within the Department of Aeronautics and Astronautics—education has been an underlying principle shaping the nature of the company through our transition to independence in 1973 and the subsequent decades.

The uniqueness of Draper as a company is due in part to our continuing dedication to the process of education. The belief that real problems are ideal teaching mechanisms has infused our culture throughout our history. Education is achieved not only by students in the formal sense, but by all Draper staff in the conduct of their work. We believe that the best way to learn technology is for people to be engaged in solving real-world problems.

Formal education programs are a key element of the culture as well. Since our inception, the range of Draper's educational involvement has included supporting graduate school education through research assistantships and university R&D programs and supporting undergraduate education via cooperative education programs and summer internships. Over the years, we have also supported a wide variety of local and national K-12 science, technology, engineering, and mathematics (STEM) programs, notably through volunteerism by our staff. Throughout our history, Draper has played a key role in the technical education of thousands of engineers and scientists.

During poster sessions for Draper Scholars, students share their research with staff from throughout the company and across disciplines—one way of stimulating innovation.

One of three objectives of the Laboratory: Advancement of education, particularly for the transition phases that lie between formal academic courses and professional practice, in an environment that does not interpose barriers between these phases in the progress of personal development.

- Dr. Charles Stark Draper, President's Message, 1971 Annual Report

FROM DRAPER FELLOWS TO DRAPER SCHOLARS

When the Draper Laboratory spun out of MIT in 1973, our educational partnership continued under what was dubbed the Draper Laboratory Fellow program. Each year, a new crop of Draper Laboratory Fellows received financial support and real-world research opportunities, working alongside project teams at one of Draper's facilities and conducting thesis research under the supervision of a senior Draper technical staff member and a university faculty member.

Our commitment to these uniquely structured research partnerships continues today under the Draper Scholars Program, which provides tuition coverage and a monthly stipend in addition to experiential research opportunities. Draper Scholars collaborate with our senior staff members, with joint supervision from their university faculty. Over the years, the program expanded to include graduate students from multiple preeminent science and engineering academies across the nation, with active duty servicemembers representing nearly a third of students in each cohort.

Today, Draper partners with more than a dozen prestigious universities in New England, Texas, Colorado, and Florida. Each year, 60–70 graduate students undertake thesis-level R&D projects with potential application to our customers' missions in national security, defense, and space exploration. By 2033, we aim to more than triple the program, welcoming 250 Draper Scholars annually to help solve the technological challenges of our nation.

To date, more than 1,300 graduate students have completed their degrees under a research partnership with Draper. Many have since capped their careers as leaders in government, military service, industry, and academia—including several astronauts and military flag officers and two Draper vice presidents.

EXPANDING OPPORTUNITIES FOR GRADUATE STUDENTS

As an engineering innovation company, Draper is committed to providing career- and skill-enhancing internships for underrepresented minorities pursuing advanced STEM degrees. In 2018, Draper joined the National GEM Consortium and added annual sponsorships for graduate students from minority communities that have historically been underrepresented within STEM fields. In the ensuing years, Draper welcomed GEM Fellows from MIT, Tufts, Northeastern, Duke, the University of Michigan, and other leading universities. These Draper-GEM Fellows participated in summer internships, working closely with our experts on R&D at the cutting edge of autonomy, wireless communication, biomechanics, and other fields.

As the vanguard of advancements in foundational research and applied engineering, the graduate students Draper sponsors through these programs help our own engineers and scientists tackle vital global problems. Collectively, this research and work has contributed significantly to the world's body of scientific knowledge, while feeding a steady stream of well-educated engineers and scientists into the national reservoir of talent.

Summer students are pictured with their Draper staff advisors and the solar plane they built and field tested in 2019.

SUPPORTING UNIVERSITY-BASED RESEARCH AND DEVELOPMENT

For decades, Draper has sponsored advanced research on college campuses around the country through competitively awarded funding to university-based principal investigators (PIs) pioneering research in fields that align with Draper's interests. This funding provided to these PIs supports the thesis research of their students. Investment in these research programs not only provides Draper with a direct link to the most advanced research available but also supports the next generation of engineers as they pursue graduate work in university laboratories.

Undergraduate education programming at Draper began with Cooperative Education Programs at Northeastern University and MIT and has expanded to include technical summer internships and co-ops for student engineers from the nation's top colleges—including the Naval Academy, Air Force Academy, and West Point. More than 2,400 students have held co-op positions at Draper over the years, and many have gone on to become senior Draper staff members.

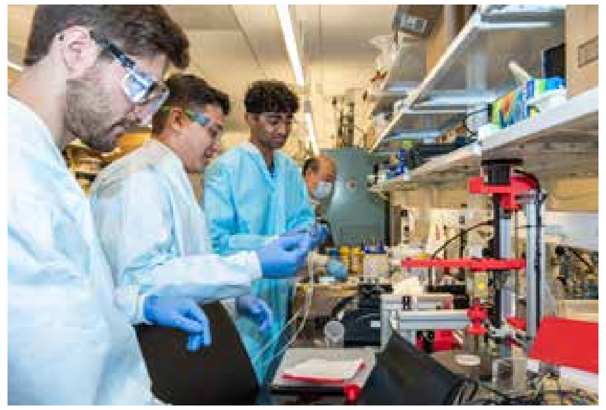
Since 2012 Draper has sponsored a Technical Challenge Competition in partnership with the fall regional conference of the National Society for Black Engineers, awarding scholarships to graduate and undergraduate students for innovative technical approaches to real-world problems. Our commitment to fostering diversity in STEM fields expanded in 2021, as Draper welcomed students under the Patti Grace Smith Fellowship and the Brooke Owens Fellowship as interns in our Space Systems program office. Both fellowships support the participation of women in STEM careers.

K-12 OUTREACH AND INTERNSHIPS

To help feed the pipeline of students who ultimately pursue degrees and careers in science and engineering, Draper staff members engage in a variety of outreach activities for K-12 students.

This includes volunteering to support students and teachers at local and national events, including U.S. FIRST Robotics, National Engineers Week, science festivals in Cambridge and St. Petersburg, USA Science & Engineering Festival, Massachusetts State Science and Engineering Fair, and Smithsonian Institution events.

In addition, Draper staff have participated for years in an email pen pal program with students in the Cambridge public school system to foster interest in STEM.



Summer interns work together on projects in Draper's bioengineering laboratory.

DRAPERSPARX

Recently, Draper launched a partnership platform to help startups and small businesses develop high-value innovations that solve critical challenges to our national security.

Dubbed DraperSPARX, the platform is a secure, collaborative digital environment that supports rapid prototyping, validation, and demonstration. Working with venture capital and private equity firms, we provide DraperSPARX partners with access to facilities, experts, and networks to help accelerate government adoption of validated technologies.

The focus of DraperSPARX aligns with our long-standing areas of expertise, including warfighter safety and homeland security, and furthers our commitment to vital national interests.

A VITAL LINK TO THE FUTURE

The relationship between Draper and technical education is vital and irreplaceable. By continually advancing the leading edge in the areas in which we work, Draper also enhances the professional development of our technical staff, enabling them to meet the immense challenges facing our nation today and in the future. Draper's continuous pursuit of excellence is inextricably linked to the development of new technical knowledge through the transition of academic research into solutions for real-world problems.

This replica of the Draper Prize medal accompanied Col. Kenneth Cameron, USMC, astronaut and former Draper Fellow, aboard Space Shuttle flight STS-37 in 1991.

THE DRAPER PRIZE

> *This prestigious award honors those engineers who, often against great odds, explore a new world of possibilities. Pioneers like Pierce and Rosen have taken that exploration further by transforming scientific knowledge into improvements in communication, mobility, education, environment, security and entertainment—enriching our lives, broadening our minds, and increasing our opportunities to prosper.*
>
> - President William Clinton
> February 20, 1996

The Charles Stark Draper Prize was established and endowed in 1988 in tribute to our founder. Awarded biennially, it honors those who have contributed to the advancement of engineering and to improve public understanding of the importance of engineering and technology.

Administered by the National Academy of Engineering, this international prize is the engineering profession's highest honor. It is awarded for engineering achievements and their reduction to practice in ways that have significantly impacted society by improving the quality of life, providing the ability to live freely and comfortably, and/or permitting access to information. The $500,000 prize can be awarded for achievement in any engineering discipline.

The first prize was presented by President George Bush in 1990 to Jack Kilby and Bob Noyce, the engineers who independently invented the monolithic integrated circuit. Over the years, the Prize has been given for:

- Development of the turbo jet engine.
- Inventions of satellite communications, fiber optics, the Global Positioning System, liquid crystal displays, and cellular telephony, all of which have led to revolutions in communications.
- An enabling algorithm used in speech recognition technologies.
- Numerous advancements in information technology, including the integrated circuit, the networked personal computer, the Internet and the World Wide Web, cellular network technologies, and reduced instruction set computer (RISC) chips.

The Draper Prize has also been given for engineering accomplishments drawing on the life sciences, including bioengineering for drug delivery and directed evolution.

Looking Ahead

At Draper, we envision a future that is driven by innovation to serve the nation's needs. We will advance technologies in space, electronics, biotechnology, and credible deterrence solutions. By fulfilling this vision, we will protect democracy and the American way of life.

By 2033, our roadmap is to advance technologies central to our national interest. We will redefine and enhance our human experience by reducing threats to our national security and individuals' health. We also envision a world where biometric devices can identify diseases and other biological concerns while working with medical professionals to tailor treatments before symptoms develop. We want humans living and working on the Moon, not as visitors, but as colonists and explorers who leverage Draper technologies to communicate and navigate. And we will help to ensure a secure, safe, and resilient environment supported by Draper's precision engineering solutions.

Throughout our 90-year legacy, our nation's future has relied on Draper. Formed at the intersection of scientific advancement and national imperatives, we engineer across four areas:

> **Strategic Systems**
> *Expands on our legacy of guidance, navigation, and control for strategic missions to ensure overall mission effectiveness across domains including nuclear, hypersonic, and missile defense systems.*
>
> **Electronic Systems**
> *Enables technological advancements in alternate and assured positioning, navigation, and timing; autonomy; and secured, assured, and radiation-hardened microelectronics.*
>
> **Space Systems**
> *Provides technology to support civil, commercial, and military missions from near-Earth to Cis-lunar environments.*
>
> **Biotechnology Systems**
> *Integrates precision engineering, life sciences, and physics to address the biosecurity and biomedical needs of the nation.*

As a disruptor, Draper helps our nation to maintain a strategic advantage on Earth and beyond our solar system. Our capabilities across disciplines will continue to require the highest levels of precision and timing. For us, resilience is paramount, so we enable our systems to operate reliably in austere and harsh environments with protection from radiation, cyber, and biological threats.

As the nation's steward for strategic guidance and navigation capabilities, we advance credible deterrence through novel technologies. By 2033, we will expand our mission effectiveness by leveraging operational and evolving threat analyses. Through platform-enabling solutions, we apply our expertise in inertial and navigation aiding technology, radiation-hardened parts, resilient avionics design, and mission domain knowledge. Our technology, combined with lifecycle innovation and threat awareness, will underpin our nation's ability to ensure credible integrated deterrence across the full spectrum of conflict. Draper will enable nuclear, hypersonic, and missile defense solutions deployable anytime, in any domain and under any circumstances.

In electronic solutions, we will be the preferred provider and thought leader for the most challenging applications. This includes advanced security, extreme reliability, high precision and accuracy, and peak performance in harsh environments for autonomous platforms, guidance systems, and specialized microelectronics. Draper will support all warfighting and intelligence domains by designing, delivering, supporting, producing, and enhancing sophisticated, adaptable systems and solutions that provide disruptive capabilities to our customers.

In the next decade, Draper strives to be the mission-essential provider to pioneer Space capabilities. We will increase our nation's space expansion by developing and deploying advanced technology solutions for precision sensing; guidance, navigation, and control; hardened instrumentation; and mission autonomy. We want to help the United States win the new space race as humanity reaches beyond Earth's orbit, to the Moon, the planets, and the deep space beyond.

Additionally, by 2033, our Biotechnology Systems business will be nationally recognized. As pioneers in the industry, we will accelerate integration of transformative, first-of-a-kind solutions and thought leadership in biodefense, biotechnology, and biomedical engineering. Draper solutions will range in maturity from early innovation to advanced development. We will address growing threats to our nation's security and health through classified, contained, and clinical work.

Focused on the future, we will disrupt the status quo, solve problems, and lead in excellence. Draper's mission-focused culture and our unrivaled innovation engine will advance the nation by supporting our government and industry partners.

Draper NXT.

50 Years as an Independent Engineering Innovation Nonprofit

90 Years of Outstanding Innovations and Service to the Nation

1933

Charles Stark Draper, Research Associate at MIT, led work at the Aeronautical Instrumentation Laboratory (IL) credited as notable contributions in the field in the MIT President's Report for 1933-34.

1940

Charles Stark Draper's early work on fire control led to his first **experiments in inertial navigation,** detailed in a 1940 MIT doctoral thesis by Walter Wrigley, one of Draper's students.

1942

The Lab's **Mark 14 Gunsight** first was used by anti-aircraft gunners aboard the USS North Carolina during the battle of Stewart Island. It was the first of Draper's designs that used the "disturbed-line-of-sight" principle.

1944

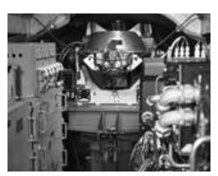
The Laboratory began to work actively on the **A-1 aircraft gun-bomb-rocket sight**. Ultimately, it became the A-4 gunsight used in the Korean War on F-86 Day Fighters.

1947

The Instrumentation Laboratory developed the **single-degree-of-freedom, rate integrating, floated gyroscope**. It enabled a stabilized platform and led to the development of high-performance gyros for ballistic missile guidance, Apollo, Submarine Inertial Navigation System (SINS), and satellites.

1949

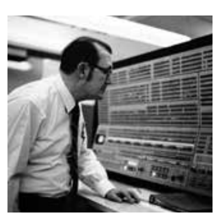
The **first celestial-aided inertial navigation system, FEBE,** was demonstrated by the Instrumentation Laboratory in an Air Force B-29 aircraft. A predecessor to the Space Inertial Reference Equipment (SPIRE), FEBE used stars as reference points to improve navigational accuracy.



1953

Dr. Hal Laning developed the first **compiler program** written to translate mathematical notation into a usable program for a computer. He began the effort in 1952 and achieved an operational program in 1953.

Space Inertial Reference Equipment (SPIRE) guided the first **coast-to-coast airplane flight** without the aid of a pilot—the first working implementation of inertial navigation for a cross-country trip.



Dr. Hal Laning

SPIRE

1954

The Lab developed an **inertial guidance mechanization**, including new guidance theory and equations, that offered a superior, nonjammable system to control ballistic missiles autonomously without broadcasting their positions. It was first used in the Thor Intermediate Range Ballistic Missile (IRBM).

The **Marine Stable Element (MAST) system**, a gyroscopic compass and a stable vertical unit combined into one instrument, was tested at sea. Some of MAST's technology later would be incorporated into SINS and missile guidance system designs.

Inertial guidance mechanization

MAST

1955

The Instrumentation Laboratory delivered an **experimental SINS** to the Bureau of Ships. The SINS was intended for submarines that would carry Polaris missiles.

1957

MIT IL was given a sole-source contract to develop the guidance and on-orbit control system for the **WS-117L satellite vehicle** based on the MIT IL SINS. That program ultimately led to the first U.S. reconnaissance program and the Corona spacecraft.

Development began of the **Floated Inertial Measurement Ball (FLIMBAL)**, which would place all the inertial instruments and the associated electronics of a self-contained, all-attitude system inside a floated sphere.

The U.S. Navy issued a contract to design, model, test, and document an **all-inertial guidance system for the Polaris missile**, beginning the long relationship between the Laboratory and the Navy Strategic Programs Office.

Sped up by the Soviet launch of the Sputnik satellite, the first successful test flight of a U.S. **Air Force Thor IRBM with all-inertial guidance** was held later that year. The Instrumentation Lab provided inertial guidance design and consulting support to industry.

1959

The **Mars probe** concept developed by the Instrumentation Lab led to a NASA contract. The breadboard model developed later became the baseline for the Apollo computer's architecture and functions, including navigation and control.

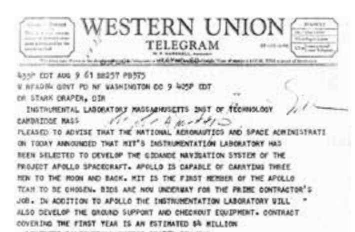
1960

A **Polaris A1 missile** was launched for the first time, successfully, from a submerged submarine. Deployed with the MK1 guidance system designed by the Instrumentation Lab, Polaris A1 had a range of 1,200 nautical miles.

1961

President John F. Kennedy committed the nation to put a man on the moon by the end of the decade. The Lab received the first major contract awarded by NASA for the **Apollo project**, which was for the guidance and control system.

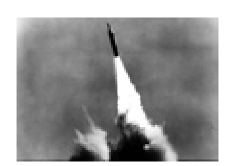
The **U.S. Air Force Titan II missile** was successfully tested. Its inertial system was built by industry based on a prototype Instrumentation Lab design. MIT's guidance system for Titan was a development from Thor's IRBM system.



1962

When the **Polaris A2 Fleet Ballistic Missile** was deployed, its guidance system, designed by the MIT Instrumentation Laboratory, enabled the missile to reach a target 1,500 nautical miles away from launch point.

The first research at the Instrumentation Laboratory into **strapdown navigation systems** was reported on in a student's ScD thesis: *Theoretical Analysis of Gimballess Inertial Equipment Using Delta-Modulated Instruments* by Thomas Wiener.



1963

The first flight of **U.S. Air Force Minuteman II missile** with the NS-17 guidance system containing a Pendulous Integrating Gyro Accelerometer (PIGA) designed by the Instrumentation Laboratory occurred.

1964

The **SINS MK IV MOD 2** was tested at sea. In development since 1960, it had improved technology from the prototype SINS.

The Polaris A3 fleet ballistic missile was deployed aboard USS Daniel Webster (SSBN 626) with the Instrumentation Laboratory-designed MK2 guidance system. The missile's range was 2,500 nautical miles.

1968

The Poseidon (C3) Fleet Ballistic Missile, the successor to Polaris for U.S. Navy, was first flight tested with the Lab-designed MK3 guidance system.

The **Apollo 8** crew orbited the moon in a craft using a guidance and control system designed by the Laboratory.

1969

Apollo 11 made the historic first manned moon landing using the onboard computer guidance, navigation, and control systems designed by the Instrumentation Lab for both the Command Module and the Lunar Module.

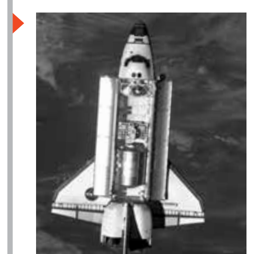
1970

The Instrumentation Lab was renamed **The Charles Stark Draper Laboratory**, a division of MIT. MIT President Howard Johnson announced **a plan to divest Draper Laboratory.**

Draper Lab was asked to provide designs for the **Space Shuttle avionics system**; contract was received in 1971 from NASA. Over time, Draper's role grew into sole responsibility for the design of the Space Shuttle's on-orbit flight control system and its backup flight control software.

The Laboratory delivered the Integrated Control and Display system to the U.S. Navy for the first of two **Deep Submergence Rescue Vehicles (DSRVs)** that launched that year.

The **Apollo 13 crew was rescued** after an onboard explosion. Draper-developed contingency autopilot software in the Lunar Excursion Module's (LEM) computer ensured stable control of the combined LEM and Command and Service Module during the trajectory correction maneuver to return to Earth.



DSRV

1971

The U.S. Navy **Poseidon C3 ballistic missile** using Lab-designed MK3 guidance system was deployed on the USS James Madison.

U.S. Navy's Special Projects Office (SP) gave Draper Lab overall design and development responsibility for the guidance system for the **Trident I missile**. The new design would use a star-tracker system to improve accuracy.

1972

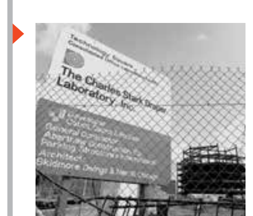
The third of four satellites of NASA's **Orbiting Astronomical Observatory** went into orbit; it was the first to feature a Draper-designed Inertial Reference Unit containing three floated beryllium gyros (2FBGs).

The first successful flight test of an aircraft completely under the control of an electronic **digital fly-by-wire control system,** designed by Draper Lab and NASA Dryden, was accomplished.

1973

The Laboratory became an independent, nonprofit corporation, The Charles Stark Draper Laboratory, Inc.

Skylab began two years of space experiments, including three manned flights to Skylab employing Apollo Command Modules. Draper Lab developed the algorithms used for Skylab's guidance and control package.

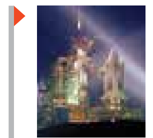


1979

U.S. Navy Fleet Ballistic Missile Trident I (C4) containing Lab-designed **MK5 guidance system** was deployed aboard submarines.

1981

The first launch of a **NASA Space Shuttle** occurred with a Draper-designed guidance, navigation, and control system and backup flight system. Draper later upgraded the system for mission needs (e.g., Hubble Space Telescope Servicing Mission in 1993).



1983

The first test flight occurred of the **U.S. Air Force MX Missile**, later deployed as Peacekeeper, with a Draper-designed Advanced Inertial Reference Sphere as the inertial measurement unit in the guidance system.

1984

The **first kinetic kill intercept** of a mock ICBM reentry vehicle occurred in exoatmosphere. Draper Lab, which had provided independent analysis to the government throughout the program, led a review committee for the Homing Overlay Experiment program before this test flight

1986

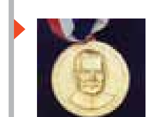
As a key member of the Delta-180 team, Draper Laboratory analyzed navigation, sensor filtering, guidance design, and software that enabled demonstration of the first **kinetic energy intercept** of a ballistic missile during its boost phase.

1987

Draper Lab was first to measure angular rate with a silicon **Microelectromechanical System (MEMS)** double-gimbal gyro, a MEMS Foucalt gyroscope.

1988

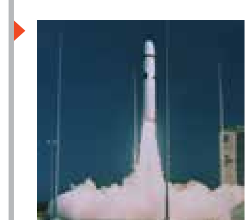
The Charles Stark Draper Prize was established in memory of the Lab's founder by the National Academy of Engineering to increase public awareness of the contributions of engineering to society's well-being.



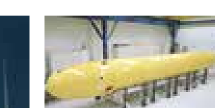
1990

The U.S. Navy Trident II (D5) Fleet Ballistic missile was deployed with the Draper-designed MK6 guidance system. The MK6 had been flight tested successfully aboard a Trident II missile in 1987.

The first of two Draper-designed **Unmanned Undersea Vehicles** began at-sea testing for DARPA. These autonomous test beds were designed around Draper's fault-tolerant processor and vehicle control architecture and were used to test mission package



Trident II (D5)



UUV

1992

Draper demonstrated the first **micromachined silicon tuning-fork gyroscope**, with noise of 500 degrees/hour per square root Hertz. This success stimulated research that led to military and commercial applications.

1993

The navigation system for the **USS Dolphin,** a deep-diving U.S. Navy research and development submarine, was delivered. Draper later upgraded the system.

1994

Draper **Multichip Modules (MCMs)** were first delivered; Draper began its work on MCMs in 1987, interested in the technology's potential to miniaturize systems through more-compact packaging of integrated circuits.

1995

The first docking of the **Space Shuttle and the Russian Space Station Mir** on June 29, 1995, successfully demonstrated work begun a year earlier by Draper to redesign the Shuttle's on-orbit flight control system for that mission.

The WM Keck Foundation awarded $4.5M to fund a three-year collaboration among Draper, MIT, and Mass. Eye & Ear Infirmary, establishing the **Keck Neural Prosthesis Research Center**. This became a cornerstone of Draper's future biomedical engineering activity.

Russian Space Station Mir & Space Shuttle

1996

The first **all-silicon sensor-based inertial measurement unit,** designed by Draper Lab, was gun-launched as part of the Extended-Range Guided Munition Demonstration Program.

Under the **Precision Guided Airdrop System (PGAS)** program, a first-of-kind autonomous guidance, navigation, and control capability for parafoils was demonstrated. PGAS was able to navigate via an onboard combination of an inertial navigation system and GPS.

1997

Draper delivered the tactical hardware and software of the **Integrated Control and Display System for the Advanced SEAL Delivery System** to the U.S. Navy.

The first completely **"fly-by-wire" fault-tolerant submarine control system** for the U.S. Navy began sea trials on SSN21 Seawolf. Draper developed and built the fault-tolerant ship control computers and I/O units, and also developed the software for the operating system and redundancy management.

1998

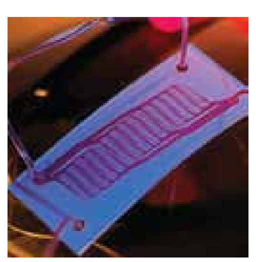
Draper upgrades to the on-orbit flight control system it developed for the Space Shuttle were utilized for the first **International Space Station assembly flight.** Draper-developed upgrades provided robust stability, improved control, and operational simplifications.

The first prototype of a micromachined **Differential Mobility Spectrometry (DMS)** system was fabricated and tested. The scope of this work led to miniaturizing DMS technology. The effort was part of a collaboration with New Mexico State University.

International Space Station

2001

Draper reported on its work on the **first artificial blood vessel network** using MEMS technology at MicroTAS 2001 Conference.



2003

Draper began an expanded role as both the **Programs and Systems Integrator for the entire U.S. Navy Trident II (D5) missile guidance program.** It initiated development of MK6 MOD 1 guidance system, the first strategic missile guidance system employing solid-state gyros.

2004

Draper-designed software enabling autonomous collection of intelligence, surveillance, and reconnaissance data via an unmanned undersea vehicle was demonstrated in ONR's **Maritime Reconnaissance Demonstration program**.

2005

A belt-mounted **Personal Navigation System** demonstrated the ability to determine location without GPS using a MEMS inertial measurement unit and a miniature Doppler velocity sensor, both developed by Draper.

MCM technology at Draper completed its essential transition from a promising laboratory technique to an economically viable production process. Key to this advance were the application of machine vision to laser-drilled via-hole alignment and the implementation of known-good-die testing after thinning.

2006

The Draper-designed **Inertial Stellar Compass** became fully operational onboard the TacSat-2 spacecraft—the first use of a MEMS gyro in space as part of a stellar package for spacecraft attitude determination.

Draper received its first grant as a principal investigator from the National Institutes of Health, for the **Bioengineering Research Partnership for Intracochlear Drug Delivery** with Massachusetts Eye and Ear Infirmary.

The **integrated Ultrahigh Density (iUHD)** platform concept was introduced. This packaging process exploits commercial semiconductor process equipment to create 3D stacked systems that are customizable and compatible with multiple materials and substrates.

The **Joint Precision Airdrop Mission Planner** was rapidly deployed in Afghanistan, operating on laptops onboard Air Force cargo planes. The mission planning software determines release points for dropping cargo, via either unguided parachutes or guided airdrop systems, for precision landing.

Draper demonstrated on orbit the **Zero Propellant Maneuver** capability we designed to conduct large-angle maneuvers of the International Space Station without the use of its thrusters. This reduced the number of fuel resupply missions.

Inertial Stellar Compass

2009

Draper received its first externally funded energy project, from Progress Energy, to develop a prototype, automated system that measures **combustion efficiency of coal power plants**.

To measure volatile organic compound levels in cabin air, microAnalyzers incorporating **Differential Mobility Spectrometry** and programmable compact gas chromatography were installed onboard the International Space Station. Enhanced microAnalyzers went into service on ISS in 2013.

Progress Energy project

2010

Draper delivered its first **iUHD modules**.

Draper Laboratory was inducted into the **Space Technology Hall of Fame** for developing aircraft digital fly-by-wire flight control technology in collaboration with the NASA Dryden Flight Research Center.

Draper Laboratory received the **Collier Trophy** as part of the International Space Station Team, sharing the award with NASA and other industry partners.

iUHD modules

Digital fly-by-wire

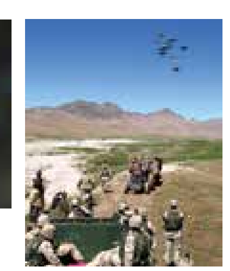
2011

A commercial version of the **chip-scale atomic clock** reached market, based on a project for DARPA that produced the world's smallest and lowest power atomic clock. Draper provided the physics package.

Draper's guided parafoil guidance, navigation, and control software was deployed in Afghanistan on the **Joint Precision Airdrop System**. The Draper flight software is now supplied as government-furnished equipment for new precision guided airdrop systems of all weight classes.

Draper delivered fault-tolerant computer design and control software along with guidance, navigation, and targeting software for **Commercial Cargo Demonstration** to the International Space Station.

Chip-scale atomic clock

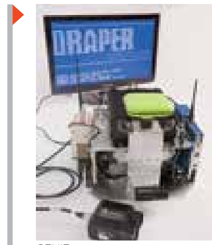


Joint Precision Airdrop System

2012

The Draper-developed **Guidance Embedded Navigator Integration Environment (GENIE)** performed its first free flight on Terrestrial Test Rocket. This test bed will enable terrestrial testing of space payloads.

The first flight test of the Draper-designed **MK6 MOD 1 guidance system** for the Navy's Trident missile was successful; the upgrade replaced all the sensors and electronics and rearchitected the system.



GENIE

2013

Cygnus flew autonomously to the International Space Station (ISS) and performed rendezvous and berthing for the first time. Draper developed Cygnus's guidance, navigation, and targeting algorithms and flight software as well as its Fault-tolerant Flight Computer Network Element and software—also used for cargo resupply services missions to ISS starting in 2014.

2014

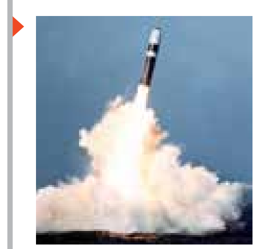
Designed for use when GPS is not available, **Draper's advanced celestial navigation technology was demonstrated on a NASA DC-8 aircraft.** It was demonstrated at sea for the first time aboard a ship in 2018.

2015

A successful live-fire test demonstrated a **self-guided 50-caliber bullet**. Draper wrote the guidance-and-control software for the bullet and for the optical sighting system for use during both day and night.

2016

Deployment began of the Draper-designed MK6 MOD 1 guidance system for the Trident II (D5) missile to the U.S. Navy submarine fleet. Draper is prime contractor for design, development, production, and deployed system support for this guidance system.



2017

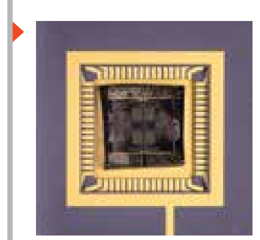
During **DOD Conventional Prompt Strike (CPS) Flight Experiment-1**, a hypersonic glide body using Draper-designed avionics and flight software navigated precisely to target during its inaugural flight test. This demonstrated an accurate hypersonic, long-range, precision-strike capability for the first time.

2019

Three years after contracting to develop its photonic beam-steering technology for automotive applications Draper successfully demonstrated a proof-of-concept **LiDAR with its hybrid integrated photonics and MEMS technology**.

Using **microphysiological systems technology** developed in collaboration by Draper and Pfizer, Inc., the companies' joint teams developed vascular, liver, and colon/ileum organ model systems over three years, delivered in 2019, to enhance preclinical drug safety and efficacy testing.

The **Orion Ascent Abort-2 (AA2) flight test** of the Launch Abort System was successful. Draper was part of the team that designed, integrated, verified, and operated the AA2 guidance, navigation, and control system as part of NASA's Artemis program.



2020

Seawolf submarine ship control **Enhanced CPU (ECPU) modules**, developed and delivered by Draper, entered service on U.S. Navy submarines. These modules, which replace the original CPU modules in the Draper-supplied 1990s ship control computer, double the fault-tolerant computing capacity to support additional mission capability and software functions.

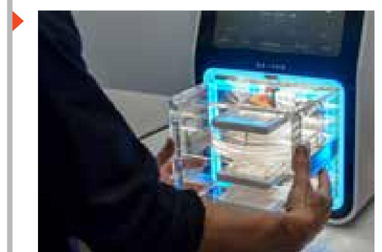
2021

Draper demonstrated the first SARS-CoV-2 infection and viral replication using a wildtype virus in a human tissue lung-on-a-chip. The experiments were conducted using Draper's **PREDICT96-ALI (airway-liquid interface) platform** and organ model.

Draper-developed **WebTAK** system provided web-based situational awareness for the Defense Threat Reduction Agency during the presidential inauguration. WebTAK is part of the Tactical Assault Kit (TAK) ecosystem, including ATAK and WinTAK, both of which Draper works with. On the original ATAK development team, Draper contributed to initial design and core software

2022

Draper delivered preclinical units of three bioprocessing modules – **acoustic separation, electroporation and viral transduction** – to Kite Therapeutics (a Gilead company) to improve Kite's CAR-T manufacturing process.



2023

Draper celebrates its 50th anniversary as an **independent, nonprofit corporation.**

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