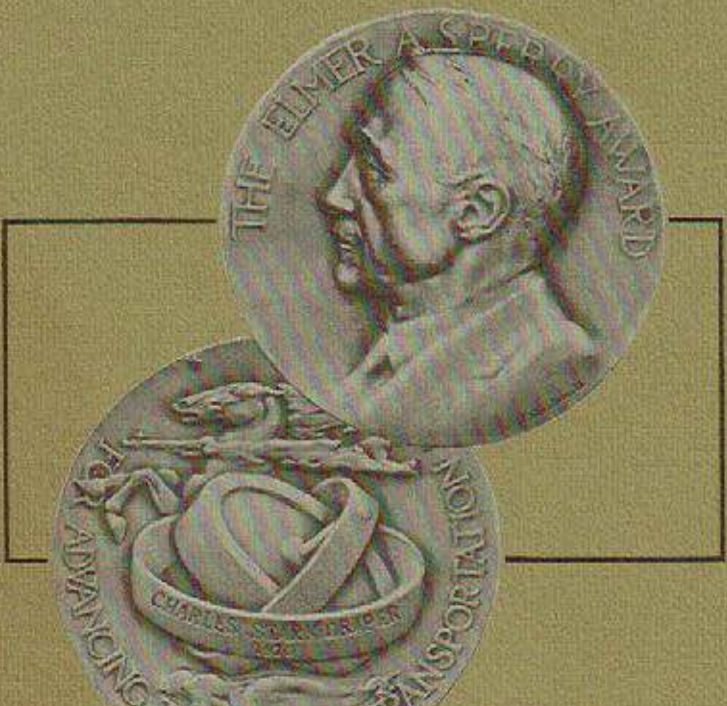
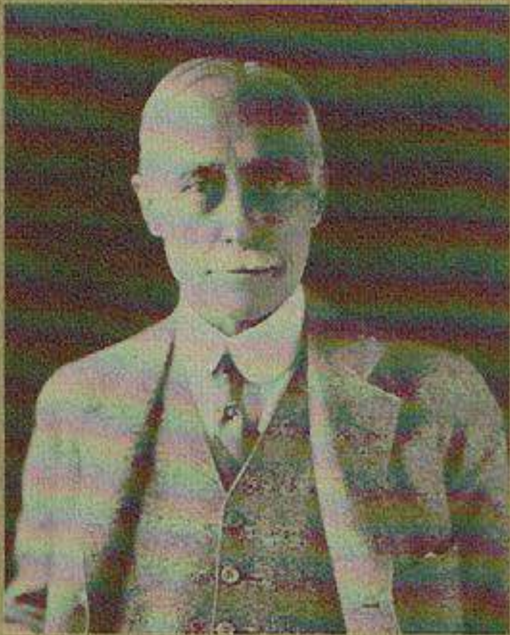
The ELMER A. SPERRY AWARD for 1970





ELMER AMBROSE SPERRY
1860-1930

FOUNDING OF THE AWARD

The Sperry Award commemorates the life and achievements of Dr. Elmer A. Sperry (1860-1930) by seeking to encourage progress in the engineering of transportation. Much of the great scope of the inventiveness of Dr. Sperry contributed either directly or indirectly to advancement of the art of transportation. His contributions have been factors in improvement of movement of men and goods by land, by sea, and by air.

The award was established in 1955 by Dr. Sperry's daughter, Mrs. Robert Brooke Lea, and his son, Elmer A., Jr., and is presented annually.

Presentation of

THE ELMER A. SPERRY AWARD FOR 1970

to

CHARLES STARK DRAPER

With Citations to the MIT Instrumentation Laboratories; Delco Electronics Division, General Motors Corporation; and Aero Products Division, Litton Systems, Incorporated.

By

THE BOARD OF AWARD

Under the Sponsorship of

The American Society of Mechanical Engineers

Institute of Electrical and Electronics Engineers

Society of Automotive Engineers

The Society of Naval Architects and Marine Engineers

American Institute of Aeronautics and Astronautics

AT THE BANQUET OF THE NINETY-FIRST ANNUAL MEETING OF THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

DECEMBER 2, 1970 • NEW YORK HILTON HOTEL • NEW YORK CITY

PURPOSE OF THE AWARD

The Elmer A. Sperry Award shall be given in recognition of –

"A distinguished engineering contribution which, through application, proved in actual service, has advanced the art of transportation whether by land, sea, or air."

1970 BOARD OF AWARD

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CHARLES STARK DRAPER

AWARD CITATION

for the Sperry Award for 1970

CHARLES STARK DRAPER in recognition of his ingenious leadership during three decades of progress in the development of inertial guidance systems and in their wide application in many areas, including space, but particularly for the successful application of the inertial guidance systems to commercial air navigation.

CERTIFICATES OF CITATION
for the Sperry Award for 1970

To the dedicated colleagues of Charles Stark Draper who served with him in the MIT Instrumentation Laboratories during the years of conception, design, construction, and testing of inertial navigation systems for flying vehicles of all kinds.

To the dedicated employes of Delco Electronics Division of General Motors Corporation for their loyal and imaginative effort and their valued contributions to the air transport industry in designing, constructing, and servicing the Carousel IV Inertial Navigation System.

To the dedicated employes of Aero Products Division of Litton Systems, Incorporated, for their loyal and imaginative effort and their valued contributions to the air transport industry in designing, constructing, and servicing the LTN-51 Inertial Navigation System.

INERTIAL GUIDANCE FOR THE AGE OF JETS

Guidance and propulsion have always been matching needs in reducing to practice man's age-old dream of limitless mobility. In the span of time from Ancient Greece, with its myths of Poseidon and Hermes, to the first decades of our century, development of propulsion means far surpassed advances in the art of vehicle guidance. The early twentieth century navigators had improved instruments and a clearer understanding of the problems needing solution than did the ancients, but the basic navigation technique – time-related observation of celestial bodies and of familiar landmarks – remained unchanged. Eighteenth century compass dead reckoning, with sun/star position updates, continued as the mode of long range marine and aircraft guidance until the introduction of radio navigation systems in the early 1940's.

When, by the mid-1940's, advances in technology heralded the high altitude jet aircraft, the atomic submarine, the ballistic missile, and the spacecraft, it became clear that a major stride in guidance technology was essential. To cope with the speeds, ranges, attitudes, and operating environments of these projected new vehicles, a totally different guidance approach was needed – one independent of external data sources and references. Inertial guidance – a simple application of the laws of Newtonian mechanics – was known in concept to meet this requirement. However, translation into practical working hardware was to present many difficulties, some seemingly insurmountable.

Before 1945, the only known application of inertial guidance was the German V-2 rocket. American efforts in the field of inertial guidance were started by the Army and the Air Force in the 1945-46 period. The problems then in need of urgent solution were: bombing from long range manned aircraft, and the delivery of warheads by both winged and ballistic missiles.

Of the various contract arrangements made by the Air Force at that time, three were destined to bear fruit in the form of complete systems carried through engineering tests. Because of doubts that sufficiently high performance could be realized using components then available or in late stages of development, these early guidance efforts were not directed toward completely inertial systems. In mid-1946, Northrop Aircraft, Inc., began developing star trackers, gyros, computers, and apparent-vertical direction indicators with the objective of providing guidance for the SNARK high-subsonic missile. The Autonetics Division of North American Aviation Corporation started development of stellar-aided guidance equipment for supersonic bombing missiles about April of that same year. In September of 1945, the

Instrumentation Laboratory of the Massachusetts Institute of Technology received a contract to design and build a stellar sighting and tracking device, a stellar computer, a three-axis stabilization device, and a time base, for use in connection with long range bombing aircraft.

As experience with design, construction, and testing of guidance systems accumulated, all of the Instrumentation Laboratory systems and several of the North American systems became completely inertial, and the complications of celestial-body tracking were eliminated. Northrop systems also moved away from all-star tracker control and toward increasing dependence on the inertial properties of gyroscopic components. Successful flight tests were made with the Northrop and North American systems in 1954.

The Instrumentation Laboratory work on inertial guidance led to the development of the first successful long range all-inertial navigation system for manned aircraft in the early 1950's, and then to the development and production of inertial guidance systems for several operational aerodynamic and ballistic missiles of the 1960's. Contemporary applications of Instrumentation Laboratory work are many – most notably the guidance and navigation systems for the Apollo Command and Lunar Modules and the Carousel IV navigator for the Boeing 747 and other commercial jet aircraft.

As with any complete product, these systems, and the research and development work underlying their design, are the result of dedicated effort on the part of many individuals from many organizations. Few, however, have contributed more or inspired and influenced so strongly the contributions of others as has Charles Stark Draper. Organizer and director of the Instrumentation Laboratory from its beginning in the 1930's, Dr. Draper's professional achievements form an inextricable major part of the story of inertial guidance in the age of jets.

Aircraft Instruments Work with Elmer A. Sperry, Jr.

Draper became interested in flying in 1918 after a few short hops in a World War I "Jenny" airplane. Upon completion of undergraduate work at MIT in 1926, he accepted a commission as a second lieutenant in the Army Air Corps Reserve and learned to fly at Brooks Field in Texas. He returned to MIT in 1928 to pursue a graduate degree and serve as a faculty member in the Department of Aeronautical Engineering.

During the 1930's as a licensed pilot flying his own airplane, often with only elementary instruments in the plane, Draper developed the conviction that if aviation was to realize its full potential, a completely onboard source of accurate position and direction information was needed. With strong motivation provided by this conviction, an excellent theoretical background in mathematics and physics, continued practical teaching to foster the development and expansion of ideas, and an ongoing interest in flying, Draper was well qualified to advance the technology of aircraft guidance in the years ahead.

In 1927, Draper had met Preston Bassett, chief engineer for the Sperry Gyroscope Company, and Bassett, in turn, introduced him to Elmer A. Sperry, Jr. This was the beginning of a mutually inspiring and productive relationship that extended for some 30 years. In working with Sperry to invent, build, and test unconventional flight instruments, Draper developed a real understanding of some usually obscure principles of mechanics and a clear recognition of the performance requirements for self-contained navigation systems. He also derived much benefit from opportunities provided by Elmer Sperry, Jr., to work on aircraft instrument production lines and to attend the Sperry Marine Gyro Compass School.

At the time of their meeting, Sperry was engaged in developing gyroscopic instruments for Jimmy Doolittle's blind flight work. The Sperry Artificial Horizon and Directional Gyro, which grew from this effort, represented spectacular advances in orientational references for aircraft. The boldness of the pioneering ideas incorporated by Sperry in these instruments, their excellent designs, and their operational usefulness are all demonstrated beyond a doubt by the fact that the same instruments, with some product improvements, remain standard equipment on all aircraft that operate under conditions of poor visibility.

His association with Elmer Sperry, Jr., and experience with Sperry's instruments taught Draper the fundamental importance of three concepts:

1. Gyroscopic actions provide practical means for bypassing actual mechanical supports to "look" directly at changes in vehicle orientation with respect to inertial space.

2. Highly responsive gyroscopic instruments can be produced by rapidly spinning relatively small and low weight rotors, making it practical to stabilize a reference member against angular motions of the vehicle in which it is carried.

3. The precessional response of the spinning rotor to applied torque is an excellent way of accurately aligning the reference member in an orientation convenient for guidance.

Draper also learned well that gimbal and rotor bearings based on mechanical contacts or thin film lubrication have threshold levels of erratic torque that effectively limit the performance of practical instruments. He became acutely aware that the accurate indication of large angles is made difficult by the relationships of spherical trigonometry and becomes effectively impossible if the region to be covered includes a full sphere.

With convictions reinforced by practical experience in designing, producing, and testing aircraft instruments, Draper began to carry out sponsored research projects at MIT for the National Advisory Committee for Aeronautics. From 1930 until about 1938, these projects involved instrumentation to measure pressure in the cylinders of piston-type aircraft engines and to record potentially dangerous engine vibrations. These latter endeavors resulted in the manufacture of the Sperry-MIT Vibration Measuring Equipment. Continuation of this research under joint NACA, Sperry, and Wright Aeronautical Corporation sponsorship led during World War II to large scale use of engine analyzers that measured detonation and other operating conditions in flight.

In the period of the 30's, however, little sponsorship was available for work on inertial instruments. Without support, Draper had inspired a considerable number of graduate students to choose aircraft instrument problems for their thesis subjects and to combine theory with both laboratory and flight experiments. Special equipment and flying time were paid for by Draper, who also served as the pilot for the tests. A broad range of instruments was covered, and a number of papers authored jointly by students and their professor were published in professional journals. Several students who participated in these endeavors have since become well recognized professionals in the field of aeronautical instrumentation.

During the summer of 1938, Draper, while visiting his former home in Palo Alto, California, found that the Boeing School of Aeronautics was giving courses in blind flying using the then new Link Trainer to supplement under-the-hood practice. It was customary in those days to rely primarily on the bank and turn indicator as a source of aircraft orientation information.

Consisting essentially of a ball in a liquid filled curved tube for bank indication and a spring restrained single-degree-of-freedom air spun gyro for turn indication, the device was regarded as much more reliable than the usual "amount instruments." Students were, therefore, trained to fly blind with magnetic compass, bank and turn indicator, altimeter, rate of climb meter, tachometer, oil pressure gage, engine temperature gage, and so forth. (It is worth noting that this viewpoint changed through the years, and the amount instruments, now called the bank and climb indicator and the turn indicator, are the basis of all instrument flight operations.)

Many hours of personal flying with the bank and turn indicator gave Draper intimate familiarity with the behavior of single-degree-of-freedom gyroscopes that employ the precession-under-torque rather than the rigidity-in-space possibilities of spinning-rotor devices. He was impressed by the erratic behavior of the rate of turn action for low rates because of the stickiness exhibited by ball bearings. This was annoying because it made straight flying and slow turns difficult to carry out smoothly and accurately. After considerable thought Draper decided to eliminate this difficulty by replacing ball bearings and spiral restraining springs with flat spring supports for the single gimbal and by using shear in high viscosity fluid for the purpose of damping.

Draper discussed the turn indicator ideas with his friends at the Sperry Gyroscope Company. The result was that, in 1939, chief engineer Bassett authorized the first support for gyroscopic instrument work in the Aeronautical Engineering Department at MIT. The grant was sufficient for the design and construction of two spring suspended, liquid damped turn indicator engineering models suitable for flight evaluation. These instruments were tested in Draper's OXX5 Curtiss Robin Airplane and in the Sperry Company's Lockheed Lodestar. The flight tests showed smooth indications for small rates of turn and demonstrated that orientational control in blind flight could be easily accomplished. It was decided, however, that the units did not offer sufficient advantage over the long-in-production Pioneer bank and turn indicator.

Draper, naturally, was disappointed, but, hearing that the French were having difficulty in hitting moving German tanks, suggested that his rate of turn indicators be made the basis of a gunsight which could correct for target motion during projectile flight times. Mr. Bassett and his colleagues thought the idea had sufficient merit for Sperry to fund the design and fabrication of a gunsight using the two existing turn indicators. Tests with a small caliber rifle against a moving target showed that the device could generate correct lead angles. Demonstrations for officers of the Army, Air Force, and Navy indicated the feasibility of the principles, but did not lead to further development. Only after Professor Fowler, representing the British Admiralty, witnessed a demonstration more than a year later, was work resumed on the sight, under British sponsorship.

About this same time, multiple attacks on Allied warships by the Japanese were becoming a serious threat. Without the time to train men in the complex problems of hitting rapidly moving targets, it was imperative that effective, reliable, and inexpensive antiaircraft sights requiring very little gunnery skill be immediately available to the Navy in large numbers. As it happened, several Navy officers, all of whom later achieved flag rank in their profession, were students in Draper's courses and were familiar with the operating principles and engineering concepts involved in his lead angle computing gunsights. With the help of these students, the Confidential Instruments Laboratory, as Draper's organization was renamed, was given the task of designing and building 12 gunsights, suitable for combat use, in a period of about 6 weeks. The contractual arrangements were worked out between Nathaniel McLean Sage of MIT, the U.S. Navy, and the Sperry Gyroscope Company.

It was Sage who nurtured the Laboratory in its new role of designing for high production and dealing with the problems of large organizations. In many ways, his wisdom, continued interest, and skill in organizational matters made possible the later contributions of the Laboratory.

The story of the involvement of Draper and his coworkers with aircraft fire control technology for the Navy is pertinent only in that it enabled the Instruments Laboratory to grow from a half dozen people to hundreds of employes with support levels approaching six figures. Let it suffice to say that the first gunsight, designated Mark 14, was successful and used by the thousands in ship-to-aircraft combat. It was followed by the Mark 15, the radar controlled Mark 63, and after World War II, the Gunar, and finally the X-1. All of the antiaircraft work was done by the Laboratory under subcontracts from the Sperry Gyroscope Company.

Not long after the operational usefulness of the antiaircraft gunsight had been established, one of Draper's students, Colonel Leighton Ira Davis (now Lieutenant General Davis, Retired) suggested that the gunsight principles be applied to the fire control problems of aircraft gunnery, bombing, and rocketry. This suggestion resulted in the development of the so-called Davis-Draper Gun-Bomb-Rocket Sight.

Having finished his graduate work at MIT, Colonel Davis moved to Wright Field where he entered the Armament Laboratory. While on this assignment he returned to MIT for several months, making important contributions to the new design of the sight in addition to flying operational tests. These tests showed sufficient promise, and plans were made to outfit an operational fighter squadron with the sights. Negotiations by the Armament Laboratory with a number of companies in 1943 resulted in a contract with the AC Spark Plug Division of General Motors in Flint, Michigan, to build a lot of 16 sights, now designated the A-1 gun-bomb-rocket sight. Work was well underway when V-J day occurred and the project was abandoned.

The Air Force continued to be concerned with operational possibilities of the A-1 sight, however, and during the 1946 to 1950 period authorized a number of design and production projects for the Sperry Gyroscope Company and for the AC Spark Plug Division. As a result of this activity, a modified unit called the A-4 was ready for the F-86 Day Fighters that competed with Russian MIG's in Korea.

While Draper's experience with fire control instruments did not directly provide mechanization for navigation and guidance, it did build an excellent background for the stringent performance requirements of these fields.

The First Successful Long Range All-Inertial Guidance Systems

In 1945, the Air Force Armament Laboratory under Colonel Davis, and with the help of Dr. J. E. Clemens and Dr. Ben Johnston, provided the Instrumentation Laboratory with its first significant sponsorship in the area of aircraft navigation, guidance, and control. Because the Armament Laboratory's assignment was to deal with weapon systems, while another laboratory held responsibility for navigation, the first contract between the Air Force and MIT was for a Stellar-Inertial Bombing System to be researched, designed, and flight tested by the Instrumentation Laboratory. The specification was directed toward a target miss distance in navigation of about 1 mile at the end of a 10-hour flight.

This specification meant that the accumulation of alignment error, or drift, of the gyroscopically stabilized reference member could be no more than one-tenth of an arc-minute per hour. Assuming a drift specification for the turn indicator gyroscopes of about 12 degrees per hour, allowable drift for the new stellar-inertial system instruments had to be about four orders of magnitude less than that acceptable for aircraft instruments. A similar performance comparison for accelerometers showed that the force-sensing components for the new system would also require about a four order of magnitude improvement.

Facing these considerable advances in performance, it was realized that radically new sensor designs were needed. The studies, the arguments, the trial designs, the building and laboratory testing of components and systems, and, finally, the flight testing all occupied several years and would require more space for proper discussion than is available here. However, the more significant departures in mechanization from that of conventional aircraft instruments are cited to show the extent of Dr. Draper's pioneering in what has since become accepted practice for inertial guidance systems.

In general, Draper conceived the overall features for self-contained guidance systems, suggested principles for subsystem and component designs, and, in the beginning of the work, made drawings and personally carried out laboratory tests. He made key flights with completed equipments, explained principles, worked with the creative and highly motivated laboratory staff to advance all phases of guidance technology, and in general helped to the best of his ability with the organizational, financial, and management problems of sponsored research in modern times.

Remembering his earlier experiences with Elmer Sperry's instruments, Draper suggested and helped put into practice the use of servo-driven reference members to greatly reduce the uncertainty-producing effects of gimbal bearings. This approach allowed precise orientational control by means of signal generators attached to the precessional axes of the sensing instruments. Draper greatly reduced gimbal-support difficulties by enclosing the gyro rotors in hermetically sealed containers floated in dense and very viscous fluids. Following the pattern originally established in the gunsights, he used viscous action to produce output signals with magnitudes proportional to the rotational disturbances sensed by the gyroscopes.

Because of the coupling actions inherent in two-degree-of-freedom devices, difficulties in balancing, and other known technical problems, Draper and his colleagues decided to follow the general pattern of gyroscopic turn indicators and devote full effort to the development of single-degree-of-freedom gyroscopic units for the control of servo-driven reference members. The rivalry between proponents of two-degree-of-freedom and single-degree-of-freedom gyro units for inertial reference stabilization is of long standing. Both configurations have provided working systems of general purpose quality. A notable current example of the two-degree-of-freedom approach is the inertial navigator produced in both military and commercial versions by Litton Industries.

In addition to stabilization gyroscopes for orientation-holding purposes, inertial systems require specific-force-sensing instruments, frequently termed accelerometers, to furnish position change information. Specific-force sensors developed by Draper in the Instrumentation Laboratory followed patterns generally similar to those of floated single-degree-of-freedom gyros. The only essential change was that of substituting an unbalanced or pendulous mass for the spinning rotor within the float. Early instruments used a freely suspended mass, and the deviation of the mass from its neutral or null position was taken as a measure of vehicle acceleration. Because such an instrument was suitable for measuring only very low acceleration levels, a torque restraint was added, and the amount of torque required to hold the mass at null became the measure of acceleration. Later versions of the pendulous torqued accelerometer employ digital pulsing techniques, a count of pulses giving vehicle velocity – the time integral of acceleration. This type of instrument became known as the PIPA or Pulsed Integrating Pendulous Accelerometer.

Another specific-force-sensing mechanization developed at the Laboratory makes use of a gyroscope with an unbalanced float mounted in a single-axis servo drive. The gyro is rotated about its sensitive axis to develop sufficient precessional torque to null the inertia reaction torque resulting from vehicle accelerations. Because the angle of rotation is a measure of vehicle velocity, the pendulous gyro configuration has come to be known as a PIGA or Pendulous Integrating Gyro Accelerometer.

Once the development of inertial sensors and other system components – such as servo drives, amplifiers, and time drives – was sufficiently underway to assure general acceptability, work began at the systems level. The first of the guidance systems developed by the Instrumentation Laboratory was a geometrically stabilized automatic star tracker, code named Febe (a variant of Phoebus Apollo, the sun god). Flight testing of the Febe system, begun in the spring of 1948, showed that the chances of achieving satisfactory solutions for the problems of inertial guidance were good enough to justify further development.

Three successful inertial system development programs based upon Febe results were begun within the following 2 years. Two of these – the MAST (Marine Stable Element) program, under Navy sponsorship, and the SPIRE (Space Inertial Reference Equipment) program, under Air Force sponsorship – were carried out by the Instrumentation Laboratory. The third, a program paralleling SPIRE, code named SIBS (Stellar-Inertial Bombing System), was conducted by the Milwaukee Operations of General Motors Delco Electronics Division – at that time the Milwaukee operations of the AC Spark Plug Division – under Draper's guidance[1]. MAST, a combination gyrocompass and stable vertical reference, underwent successful shipboard testing in 1953.

SPIRE was started in late 1949. This fully inertial system was given its first transcontinental test flight in February 1953. On the basis of the encouraging results, design of a system of reduced weight and improved performance, called SPIRE, Jr., was begun in mid-1953, culminating in an inertially guided transcontinental flight in March 1958, which received nationwide television coverage.

SIBS, the third outgrowth of Project Febe, was begun by Delco–Milwaukee in 1950. Selection of Delco was based upon the highly successful production record of that organization on the T-1 bombsight, K-14 gunsight, A1A bombing navigational computer, and – in collaboration with the Instrumentation Laboratory and the Sperry Gyroscope Company – the Davis-Draper A-series of gun-bomb-rocket sights. SIBS was to utilize the SPIRE design but incorporate stellar monitoring of inertial reference alignment, provision for inflight reference reorientation, and capability for high altitude bombing. Huge by today's standards, the system weighed nearly 2 tons and occupied most of the waist compartment of the B-50 in which it was installed. SIBS first flew in 1952, and, as one of the world's earliest successful inertial systems, helped prove the theory upon which a family of later Delco–Milwaukee inertial systems was based. In 1955, Delco completed the project and turned the system over to the Air Force for further evaluation. Navigation accuracy proved to be so outstanding that the stellar monitoring concept was abandoned and the era of unaided inertial guidance began.

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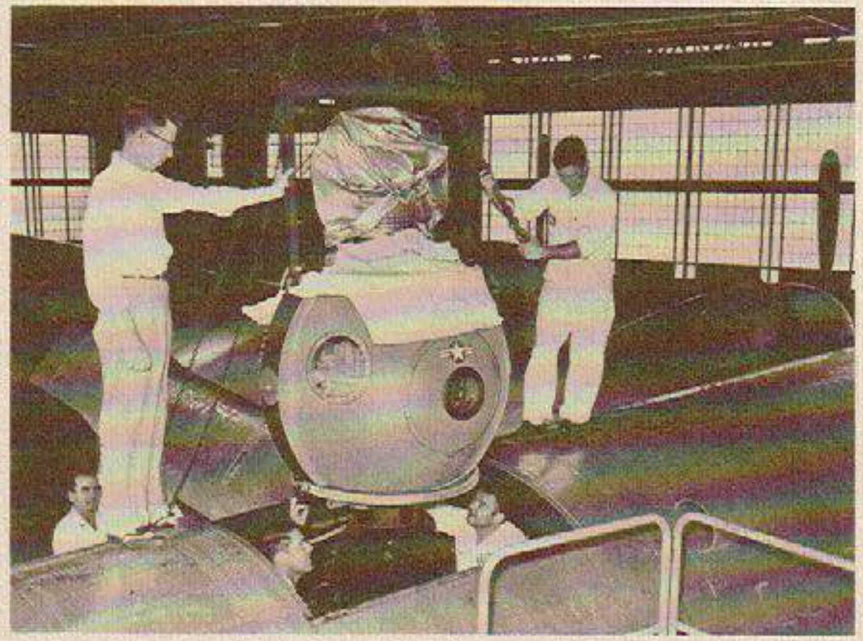
[1]Formed in 1948, the Milwaukee Operations of General Motors AC Spark Plug Division was given divisional status in July of 1965 and renamed the AC Electronics Division. In September of 1970, AC Electronics was combined with GM's Delco Radio Division to create the Delco Electronics Division.



The Stellar-Inertial Bombing System, designed and evaluated by the Milwaukee Operations of Delco Electronics Division in the early 1950's under Dr. Draper's guidance, conclusively demonstrated the practicality of inertial systems.

Guidance Systems for Defense

By 1950, results of studies and preliminary subsystem tests on the MAST project at the Instrumentation Laboratory suggested that a complete inertial navigation system for naval vessels should be feasible. Accordingly, a parallel program was begun in mid-1950 to study and develop for the Office of Naval Research a Submarine (later Ship's) Inertial Navigation System, called SINS. Completed in the spring of 1954, SINS was given preliminary tests in a van. Shipboard tests followed 6 to 8 months later, and a final report was submitted in June 1955.

Early in 1954, the Instrumentation Laboratory started work on inertial guidance for ballistic missiles as a subcontractor to the Convair Division of

General Dynamics Corporation. This effort was shifted to Air Force sponsorship early in 1955, after the Ballistic Missile Division under Lieutenant General B. A. Schriever began operations. The resulting laboratory developments supplied the basis for the inertial guidance equipment manufactured for the Thor missile by the Milwaukee Operations of Delco Electronics Division beginning in 1956.

At the time the Thor arrangement was made, Delco–Milwaukee was already under contract to the Air Force to develop all-inertial guidance systems for the Matador missile and for the Altas intercontinental ballistic missile. The Matador program resulted in the first successful inertially guided flights of an air-breathing missile. The system was later produced in quantity by Delco–Milwaukee for deployment in the TM-76B Mace missile, as the Matador was renamed.

The emphasis placed in the mid-50's upon development of the intermediate range missile caused redirection of Delco's effort on Atlas to a greatly accelerated program of development and production on Thor. Using instrument and system concepts developed by the Instrumentation Laboratory, Delco–Milwaukee completed the first engineering model of the system in August 1956. The first production system was delivered to the Air Force in April 1957, and the operational test flights were made in December of that year. Thor was the first operational intermediate range ballistic missile in the free world to be inertially guided and was deployed in the United Kingdom until obviated by the intercontinental missile force developed in the 1960's.

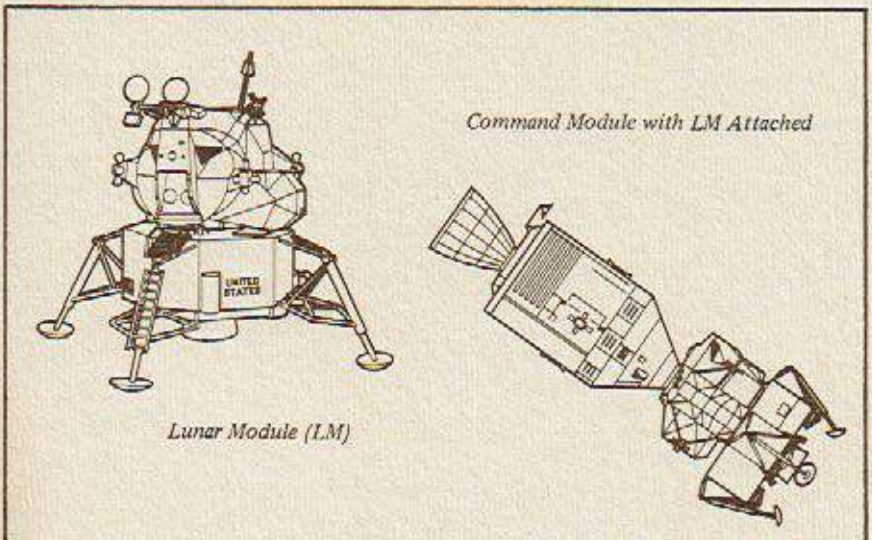
Also in 1956, Delco–Milwaukee began work under a U.S. Navy contract to develop an inertial guidance system for the submarine-launched Regulus II missile. The system was similar in design to Mace, and, like that system, used variants of the inertial instruments developed by Draper at MIT. Test flights showed that this missile was accurate for its programmed ranges of up to 200 miles.

In April 1959, the Air Force chose Delco–Milwaukee to develop from Instrumentation Laboratory experimental model plans an inertial system for the Titan II intercontinental ballistic missile. The first system was delivered 20 months later, and the first inertially guided Titan II flight, made in July 1969, traveled 5,000 miles down the Atlantic Missile Range with virtually perfect accuracy. This new weapon provided the United States with an underground-launched, long range deterrent power. Deployment of the Titan II missiles was completed at three sites in continental United States by 1964.

A year before Titan II deployment, the Milwaukee Operations of Delco Electronics, under Air Force contract, began to apply the T-II guidance system to the Titan III space launch vehicle. Deliveries of Titan III inertial systems were started in December 1963, and the first successful flights were made 9 months later. The Titan III inertial guidance system has since had many successes, including the placement of as many as eight communications satellites in near synchronous orbit in a single shot on three different occasions. Nuclear detection satellites have also been successfully placed in precise orbit by the system.

Inertial Guidance and Navigation for Project Apollo

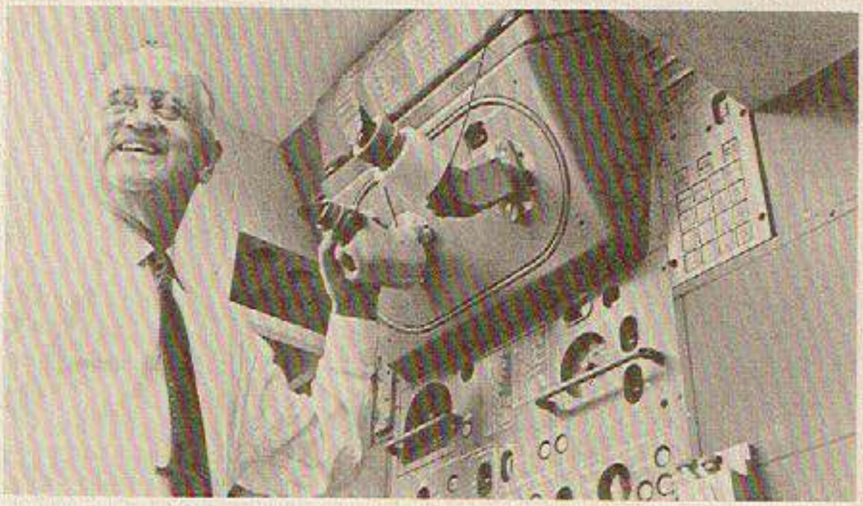
In 1960, the Instrumentation Laboratory, as a result of negotiations by Dr. Draper, received a contract from the National Aeronautics and Space Administration to develop, from gleam-in-the-eye theory to successful operation, the guidance and navigation systems for the Apollo manned lunar landing mission. Design work was started immediately, and manufacturing information became available some 2 years later.



Apollo Space Vehicles

In February 1962, as a result of Delco Electronics background in inertial guidance technology, NASA selected this General Motors division as the prime industrial contractor to build the guidance and navigation (G&N) systems for all Apollo flights. One such system was required aboard the command vehicle, while another unit, modified for landing operations, was needed in the lunar lander. Both systems were designed by the Instrumentation Laboratory under Draper's leadership.

The first flight of an Apollo guidance and navigation system was successfully made on 25 August 1966 in an unmanned mission, with a Saturn I-B rocket providing the boost. On 9 November 1967, as part of the Saturn V initial flight test, the giant rocket boosted the Apollo craft into orbit. The G&N system performed well within specifications. Apollo 7, the first manned mission, was flown in earth orbit in the fall of 1968, with the G&N system working well. Finally, in December 1968, on man's flight to the moon, Apollo 8 was successfully guided into lunar orbit with a safe return to earth by the Command Module G&N system.



Dr. Draper is shown with a model of the guidance and navigation system his laboratory developed for Project Apollo. Delco Electronics serves as prime contractor for manufacture of the system. The optical subsystem is manufactured for Delco by Kollsman Instrument Corporation and the onboard computer by the Raytheon Company.

During 1969, Delco-built G&N systems guided the Apollo 11 and 12 flights from earth to moon, to lunar landings and subsequent rendezvous, back to earth, into the critical reentry corridor, and finally to accurately positioned splashdowns in the Pacific Ocean.

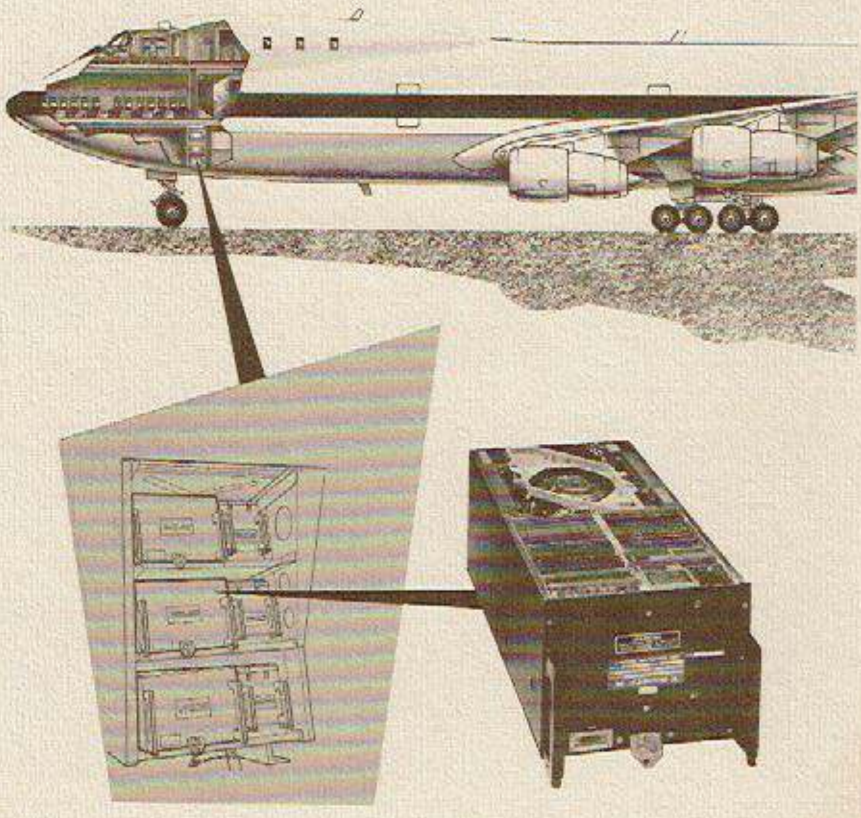
On the Apollo 13 mission, the Apollo G&N systems proved their versatility under emergency conditions. When the power loss in the Command Module forced the shutdown of the G&N system in that vehicle, the G&N system in the Lunar Module was made to assume a role far beyond its normal moon landing assignment. First, the system controlled the attitude of the spacecraft and the engine burn that put the spacecraft back on a free return trajectory to earth. Then it determined the 4-minute, 20-second engine burn that accelerated the spacecraft's return to earth by 10 hours, and, finally, it accurately guided the astronauts back to the earth – all tasks the Lunar Module system was not scheduled to handle.

Before entry into the earth's atmosphere, the Command Module G&N system was powered up, using battery energy. Although this system had been exposed to temperatures lower than those for which it was designed, it worked flawlessly, guiding the astronauts through the narrow entry window and to a precise landing in the Pacific.

Inertial Guidance Comes to Commercial Aviation

In mid-1967, the airlines issued ARINC Equipment Characteristic 561, setting forth the basic requirements of an inertial navigation system intended specifically for commercial transport aircraft. Two companies responded to the specification. The Aero Products Division of Litton Industries offered a commercial version of their LTN-51 inertial navigator for military aircraft, and Delco Electronics Division of General Motors offered a system – called Carousel IV – based on their system under development for the Boeing 747. Both systems met airline requirements and found wide acceptance in the industry. The following equipment design and operational results in the commercial practice of inertial navigation are cited from the experience of Delco Electronics, primarily because this company has been closely associated with Dr. Draper and his Laboratory for over 25 years. The fundamental ideas applied in Delco's Carousel IV were derived to a considerable extent from this association.

Factory installed on the Boeing 747, Carousel IV consists of three principal units – the Navigation Unit, the Control/Display Unit, and the Mode Selector Unit. The Navigation Unit contains the geometrical reference and support electronics, and the digital computer with its memory storage. The reference comprises three single-degree-of-freedom floated integrating gyro units and three linear force balance accelerometers mounted inside a servo-controlled set of gimbals.



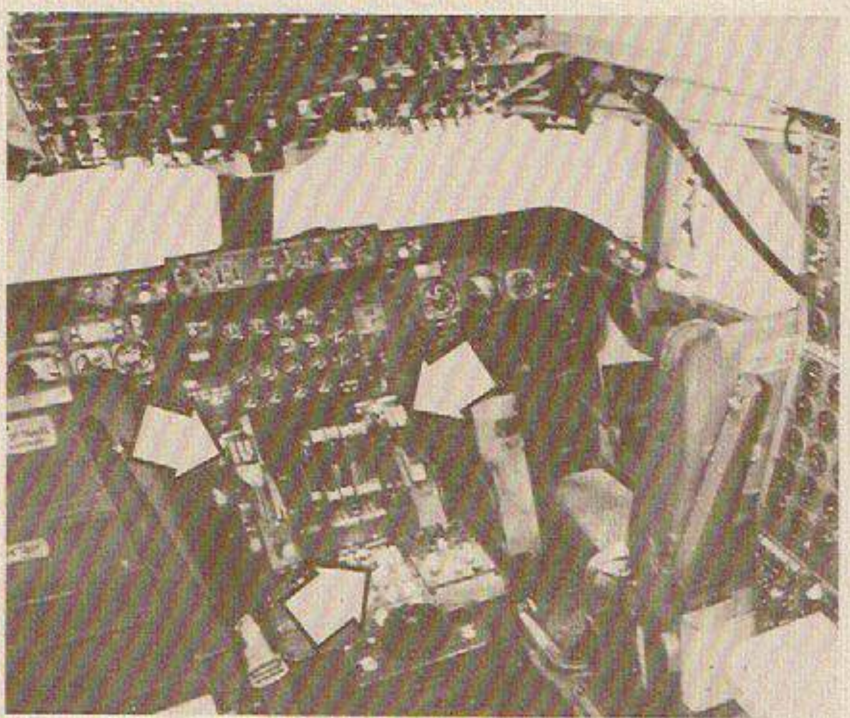
The heart of Carousel IV is the Navigation Unit, containing the sensing and computing components of the system. Three redundant units are included in 747 installations for maximum reliability.

The inner member is rotated continuously about the indicated vertical axis causing drift errors due to mechanical imperfections in the gyroscopes to effectively cancel out. It is from this rotation that the name Carousel was derived.

Digital signals from the accelerometers form the essential inputs to the computer, which solves the pertinent navigation equations in geometrical reference member coordinates based on the local vertical and north. Computer outputs, in turn, are provided to the Control/Display Unit, located in the cockpit.

The closeup of the Control/Display Unit shows a display of latitude and longitude for New York City. Control is exercised by the pilot, who turns the knobs in the lower left-hand part of the unit to command the system to display,

The Control/Display Unit is the pilot's communication link with the remainder of the Carousel IV system. The unit displays a wide range of navigation information.



Carousel IV Control/Display Units (arrows) are installed in the 747 cockpit between the pilots' seats. Mode Selector Units are located in the overhead.

for example, POS (position). He may ask for HDG (heading), wind, or other information and may shift from automatic to manual operation. The keyboard makes it possible to enter information, request results, and give detailed instructions by following procedures supplied in the operator's manual.

The third unit of each Carousel IV navigator is the Mode Selector Unit, used by the pilot to designate the general pattern of operation that he desires. The fourth unit, the Battery Unit, maintains system operation in the event the general power system of the airplane is interrupted.

Carousel IV is a unique piece of equipment. The Navigation Unit weighs just 50 pounds and is smaller than a standard size office file drawer. The gyros weigh only 8 ounces apiece. The advances that have been made in miniaturizing inertial systems are easily appreciated when the Carousel IV navigator is compared with the Stellar-Inertial Bombing System of 1952, which weighed 4,000 pounds and used gyros weighing 25 pounds each.

To assure reliability and accuracy, each 747 is fitted with three identical Carousel IV systems. This redundancy not only guards against failure of any one system, but also improves confidence in accuracy by giving multiple indications of the same information.

Before takeoff, each system automatically aligns itself to the local vertical so that the geometrical reference has one of its planes identical with the local horizontal plane. Two gyros, mounted with their input axes so oriented that they provide "gyrocompassing" action to seek out north on the ground, and a third gyro to hold this direction in flight, complete the three-axis spatial reference. With waypoint-to-waypoint and destination information inserted by means of the keyboard, the system automatically computes the best courses. The pilot may elect to fly manually using system indications, or he may choose automatic operation by connecting the system directly to the autopilot. Aircraft position in latitude and longitude is continuously available for display and is updated every six-tenths of a second.

By the turn of a switch, the pilot may command readout of: distance and time-to-go to a waypoint or to destination, track angle of the flight path, groundspeed, aircraft heading, aircraft drift angle, windspeed and direction, crosstrack distance from desired course, track angle error, and desired track angle. Each Carousel IV navigator runs a continuous self-check to review information displays for their reasonableness and to detect possible malfunctions.

Pilot or copilot operated, the system requires no human navigator, is totally self-contained, and is completely independent of radio, radar, and magnetic navigation aids, and of sun/star position inputs. Another advantage is the improved aircraft attitude information (pitch, roll, and yaw) provided. Whereas the operation of standard aircraft attitude instruments is degraded by changes in velocity, Carousel IV is effectively insensitive to aircraft acceleration so far as attitude information is concerned.

Many pilots consider the "winds aloft" information furnished by Carousel IV to be the best available. Other data sources give only averages of windspeed and direction, but Carousel IV constantly computes the difference between groundspeed and airspeed, giving an up-to-the-instant reading on windspeed and direction. When connected to the autopilot, the system accurately compensates for crosswinds, so that any course the pilot wishes to fly is automatically maintained.

An interesting new use of the Carousel IV navigator is as a taxiing speedometer. Judging taxi speeds from the 747 cockpit location, 30 feet above the runway, is difficult, and the airspeed indicator loses its effectiveness at low taxi speeds. Carousel IV, on the other hand, provides accurate information at groundspeeds as low as 1 knot.

Daily, General Motors Carousel IV navigators guide hundreds of continental and transoceanic flights, contributing markedly to the safe and reliable on-schedule operation of the air transportation industry. The system serves as the sole source of navigation data on overseas flights for many of the world's major air carriers. One such airline reports Carousel IV to be five times more accurate than the standard form of transoceanic navigation. In addition to shortening flight time and conserving fuel, this pinpoint accuracy makes possible a substantial narrowing of the present 120-mile oceanic air corridors.

The great stride in commercial air navigation which Carousel IV represents is an outgrowth of more than 20 years of inertial systems progress and achievement. From the experimental systems of the 1950's to the military, space, and commercial systems of today, Charles Stark Draper has stood at the forefront of inertial technology. In total perspective, the instrument and systems concepts Draper fostered laid the essential groundwork for what may well be the most important air navigation advance of the decade – the Carousel IV Inertial Navigation System.

ACKNOWLEDGMENT

The Elmer A. Sperry Board of Award expresses its deep appreciation to Dr. Draper and the Delco Electronics Division of General Motors Corporation for the preparation and production of this comprehensive brochure on the many uses of inertial guidance systems. The Board of Award emphasizes the fact that the 1970 Sperry Award is in recognition of the application of inertial navigation devices in commercial flights. This recognition is evidenced by the bestowal of the 1970 Sperry Medal on Dr. C. Stark Draper with certificate of citation to the MIT Instrumentation Laboratory, which was an eminent part of Dr. Draper's primary work, and to two commercial producers of inertial navigation instruments for commercially operated airplanes, the Delco Electronics Division of General Motors Corporation, and the Aerospace Division of Litton Systems, Incorporated.

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1959 to SIR GEOFFREY DE HAVILLAND, MAJOR FRANK B. HALFORD (in memoriam) and CHARLES C. WALKER and Citation to their Associates for the first jet-powered aircraft and engines.

1960 to FREDERICK DARCY BRADDON and Citation to the Engineering Department of the Marine Division, SPERRY GYROSCOPE COMPANY, for the three axis gyroscopic navigational reference.

1961 to ROBERT GILMORE LETOURNEAU and Citation to the Research and Development Division, FIRESTONE TIRE AND RUBBER COMPANY, for high speed, large capacity, earth moving equipment and giant size tires.

1962 to LLOYD J. HIBBARD for application of the ignition rectifier to railroad motive power.

1963 to EARL A. THOMPSON and Citation to his Associates for design and development of the first notably successful automatic automobile transmission.

1964 to IGOR SIKORSKY and MICHAEL E. GLUHAREFF and Citation to the SIKORSKY ENGINEERING DEPARTMENT for the invention and development of the high-lift helicopter leading to the Sky Crane.

1965 to MAYNARD L. PENNELL, RICHARD L. ROUZIE, JOHN E. STEINER, WILLIAM H. COOK and RICHARDS L. LOESCH, JR. and Citation to the Commercial Airplane Division, THE BOEING COMPANY, for the concept, design, development, production and practical application of the family of jet transports exemplified by the 707, 720, and 727.

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