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THE EVOLUTION OF AEROSPACE GUIDANCE TECHNOLOGY AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1935-1951: A MEMOIR[+]

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INTRODUCTION

Guidance technology based on automatic, self-contained, onboard equipment for vehicles moving in six degrees of freedom with respect to the surface of the Earth has progressed from non-existence to practically its ultimate potential effectiveness over a span of not much more than three decades. Beginning in the early 1940s with the German development of the V-1 and V-2 missiles, and with other achievements in the USSR, the USA, and other countries, rapid strides in effective guidance for airplanes and spacecraft have been made with substantially universal acceptance of demonstrated principles a certainty as progress continues.

A strong interest in guidance, that complex of operating functions causing a directable vehicle to move along some path to accomplish its assigned mission, began for me in 1919 at the University of Missouri, when I went on my first airplane flight in an "OX5 JENNY." I transferred from Missouri and received a Stanford Bachelor's Degree in 1922. After graduation from the Massachusetts Institute of Technology in 1926 I enrolled in the Army Air Corps Reserve Officers Training Corps and attended flying school at Brooks Field in Texas. During the last years of the 1920s and early 1930s I owned and flew an OX5 ROBIN airplane. Even though the plane's performance was low, federal regulations were not yet in operation, so it was possible to fly and experiment at will in all kinds of weather. At this time I was on the instructing staff and later the faculty of the Department of Aeronautical Engineering at M.I.T., with free and complete access to measuring

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instruments and machine tools. While teaching in aeronautics, I also worked toward a Doctor of Science Degree in Physics, with a Mathematics minor for specialization in advanced geometry and mechanics.

Because the professor who taught the courses in Aircraft Instruments left M.I.T., I was offered and accepted the assignment of teaching this subject. No systematic treatments of theory or textbooks of any kind were available. Consequently, there were no restrictions on formulating concepts, planning attacks, experiments, teaching patterns, instrument designs, and flight tests. This environment made it possible to identify, study, and find solutions for all phases of informetrics (the complex of activities dealing with the sensing, transmission, processing, evaluation and use of information) associated with the operation of aircraft. As an instructor in the Aeronautical Power Plant Laboratory, I worked under Professors C. F. Taylor and E. S. Taylor, and devised instruments for measuring engine pressures and vibration. This work attracted support from the National Advisory Committee for Aeronautics and the United States Navy, permitting me to start and maintain a small laboratory with a few assistants. These activities were established during the early years of the 1930s and in effect gave a start to the organization that eventually became the Charles Stark Draper Laboratory Division of the Massachusetts Institute of Technology.

PRELUDE FOR INERTIAL NAVIGATION SYSTEMS

Although the work with instrumentation during the 1930s was largely associated with aircraft engines, my strongest interest lay in formulating the problems associated with guidance, and designing equipment for meeting the requirements of operational situations. During and before the 1930s, radio aids for navigation were rudimentary, and, to make matters worse, owners of private airplanes usually could not afford receiving sets capable of satisfactory results. Weather reports were not generally available, and flight plans, except at the most important airports, were not required. The net result of all these circumstances meant that the private pilot could easily be caught in zero visibility, and reduced to his own resources without the possibility of help from ground stations or any other aircraft. Situations often developed in which good luck was required for survival, even if one abandoned all thought of mission accomplishment.

In several instances, a combination of poor weather and poor judgment left me with that "hopeless feeling," under conditions of substantially no visibility for seemingly very long periods of time. During these periods I was lucky to remain alive. However, after several bad experiences, and time to think over the consequences of events that occurred, I came to analyze the factors that combined to make safe flight impossible without visual contact with the Earth. The fundamental difficulty, of course, was the absence of geometrical information about the position, orientation and motion of the airplane with respect to the Earth. Two basic deficiencies were involved; first a clearly defined reference space in which orientation of the airplane could be judged, and second, a reference space, which might be the same one as that providing orientational references, from which direction of travel and linear speed of the aircraft with respect to the Earth could be estimated. Orientation, that is, roll and pitch about "horizontal" axes, and yaw, the angle from north, were needed for maintaining stabilization (angular positions about three axes well enough defined for the maintenance of safe flight while providing reference directions from which maneuvering changes in attitude and direction can be made), while the position, direction, and speed over the Earth were essential knowledge for navigation toward selected destinations.

Orientational references for the purposes of flight stabilization were first provided in practical flight instruments in 1928 with the Artificial Horizon and Directional Gyro developed by Elmer A. Sperry, Jr., for the Guggenheim Blind Flying Experiments of James H. Doolittle. The instruments gave indications showing aircraft deviations in roll, pitch, and yaw, read from dials by the pilot. With these indicated deviations, the pilot could stabilize the aircraft through his usual control movements just as he would have applied information from visual observations of the Earth's surface on clear days. The Sperry instruments were for stabilization only, and provided angular outputs good to a few degrees of angle; rough outputs by navigational standards, but adequate for maintaining control and reasonably good flight directions for human pilots. The Sperry devices did not indicate the position or velocity of the aircraft with respect to the Earth, and thus offered no direct help with navigation.

To be sure, some discussion of determining the position changes of aircraft by double integration of indicated accelerations did indeed take place among aeronautical engineers during the early 1930s. But recc ition of the high accuracy required and the need to separate effects due to gravitational fields from inertial reaction forces, led to the near-universal conclusion that the development of necessary instrumentation would involve very great difficulties. Therefore, most engineers and designers decried any attempt to develop self-contained guidance systems based entirely on Newton's Principles of Inertia as a waste of time and money.

After some fifteen years experience and study of the theoretical and engineering proglems associated with creating inertial guidance equipment, I came to disagree with this conclusion. At the same time, however, I also became convinced that creating practical means for guidance of this kind would be very, very difficult. Familiarity with state-of-the-art technology made me certain that "off-the-shelf" devices offered no real help with design or construction. Everything, the elements, components, and subsystems, would have to be imagined and created from theory, engineered, built, tested, prepared for production and operational service "starting from scratch." Substantial support for several years would be necessary if significant results were to be achieved. But support of this kind was simply unavailable during the 1930s. Consequently, beyond a few thesis projects, studies in practical "blind flight" at the Boeing School of Aeronautics in Oakland, California, some flight tests of conventional aircraft instruments, and slow but careful development of theory in mechanics with particular stress on gyroscopics incorporated into graduate student subject matter, I placed inertial guidance developments on an inactive status until more favorable conditions might appear.

For self-contained guidance systems, the fundamental problems involved using instruments to accurately indicate changes in six independent geometrical quantities, three rotations about mutually orthogonal axes, and three linear translations along these or three other mutually orthogonal axes. The general performance objectives for measuring devices to deal with the geometrical quantities essential for inertial guidance had to fall into a pattern similar to the typical behavior of watches as indicators of elapsed times after the arbitrarily selected initial instants. In addition to measurements of this kind--for changes in three angles and three translations from configurations chosen generally for convenience--indications of velocity (rate of change of position) and acceleration (rate of change of velocity) as direct or derived signals were also required for guidance system outputs.

Just as specific uses determine the performance requirements for watches, the use made of geometrical quantity sensors would set the quality of results desired from overall systems. For example, good watches may accumulate errors at rates no more than fractional seconds per day, while quartz crystal or atomic oscillators can be built to realize accuracies in the range of one part in 10^{10} and better. This wide spectrum of performance in measurements of time required many years of development before it became a matter of practice. Likewise, one could reasonably expect that some years would be needed to bring sensors for inertial quantities to corresponding levels of performance.

The performance required depends upon the following circumstances existing on our planet. On the Earth's surface, one minute of arc angle between local vertical directions means that a distance of one nautical mile (6,000 feet) has been passed on the Earth's surface. The corresponding distance for one second of arc (1/60 of a minute) is 1/60 of a mile, so that a deviation in alignment of reference coordinates to the vertical of one second in magnitude would produce a navigational indication error of one hundred feet. Therefore, the angular reference coordinates carried by an airplane had to have angular uncertainties with respect to the Earth not greater than a few seconds of arc about horizontal axes if this subsystem was to give accurate indications within a few hundred feet.

Instruments mounted on stabilized members to sense acceleration components for navigation computations would, in practice, actually sense not acceleration alone, but "specific force," the resultant of gravitational field action and inertial reaction. The signals representing specific force components would have to be "corrected" for gravitational field effects in the computing system that would also provide single and double integrations to produce indications of changes in velocity and position. If errors in position on the Earth's surface were to be limited to not more than a few hundred feet during a flying time of about one hour, specific force receivers had to have performance characteristics that allowed them to deal reliably with changes on the order of one ten thousandth or less of one Earth's gravity. I conducted various mathematical studies of the performance needed for inertial quantity sensors to serve as components for on-board aircraft guidance systems with my colleagues, notably Professor Walter Wrigley and his students during the last half of the 1930s and the first half of the 1940s, and by 1945 the instrument performance characteristics required for inertial systems were generally well recognized.

Under the impetus of World War II, radio aids for navigation received great attention and support. By war's end, civilian and military airplanes carried equipment that enabled pilots to navigate quite well under all weather conditions. Of course, positive results depended upon the cooperation of favorable radiation environments from extensive ground station networks designed to complement onboard radio equipment. However, I still remembered my days of flying without external aids and retained a strong personal interest in the challenge associated with creating self-contained, on-board guidance systems not requiring radiation contacts with external stations or points of the Earth.

Inertial guidance system developments received no significant support in our Laboratory during the early 1940s. But enemy control of vast territories during World War II soon stimulated funding of self-contained on-board equipment for aircraft guidance. Because such systems did not require help from outside stations and could not be put out of action by any measures short of actual physical destruction, World War II experiences caused Air Force officials to consider development of inertial guidance systems as essential for future capabilities. Late in 1945 Colonel (now Lieutenant General, retired) L. I. Davis, the Commandant of the Armament Laboratory, who had been my graduate student, and his chief scientist, Dr. J. E. Clemens, translated their understanding of inertial guidance possibilities into support for our Laboratory. Shortly thereafter, we began a project to design and build an experimental system. The following sections of this paper consider this work and the progress achieved during the period ending in 1951.

ACTIVITIES DURING THE FIRST HALF OF THE 1940s

Aerospace guidance was not an area that provided sponsors for Laboratory activities during the first half of the 1940s. In fact, during the last half of the 1930s the Laboratory was largely concerned with aeronautical power plant instrument projects—particularly with creating engine analyzers for long flights over water. Graduate courses on instrumentation that I taught attracted a number of Navy and Air Corps officers in addition to civilian students and, until 1939, I continued to be especially interested in the generalized geometry associated with aircraft motions and also the consequences of Newton's Laws for linear and rotational motions of rigid bodies. Progress in these areas came from preparations for lectures, laboratory work, and thesis projects associated with educational activities of the Laboratory which was then, as it always has been during its existence, an integral part of the academic section of the M.I.T. Aeronautical Engineering Department.

During the early phases of World War II, multiple air strikes at surface vessels had sad results for ships of the Allied Navies. At this time M.I.T. students, faculty, and members of the Instrumentation Laboratory became strongly concerned with developments of equipment to provide protection against such attacks. Existing guns and their associated fire control equipment had been designed for battles among surface vessels and were so large and heavy that only a small number of systems could be installed aboard even the largest ships. These gun projectiles were larger than necessary to destroy airplanes with direct hits or even near misses, while their rates of firing were slow. The equipment available for pointing guns depended on cumbersome mechanical arrangements for geometrical transformations between tracking coordinates, computing coordinates, and finally the deck coordinates in which gun movements had to occur. The control systems were not only large and heavy, but were so sluggish in action that the airplane's relatively high speed made it possible for them to complete their missions and fly safely away without much danger from anti-aircraft shells.

Designs for rapid acting machine guns firing projectiles capable of destroying airplanes by direct hits were available, with large scale production only a matter of assigning adequate resources to the task. But equipment for rapidly and effectively pointing these guns was another matter entirely, because the bulk, complexity, and cost of existing devices, even if they had been effective, made it impossible to provide control for each gun or group of guns. The general approach used for the gun design was not adaptable for reductions in weight, size, complexity, or significantly lowered costs. Consequently, during 1940, we directed our attention toward this problem of providing rapid and effective anti-aircraft fire control for machine guns carried by naval ships. Because we became involved almost exclusively with classified projects, the Laboratory was now given the new name of CONFIDENTIAL INSTRUMENTS LABORATORY.

The engineering problems involved developing fire control units (1) weighing not more than a few tens of pounds, (2) able to operate satisfactorily while mounted directly on the cradle of a firing machine gun, (3) requiring no more than a few minutes training time for normal human beings to become competent operators, (4) having good reliability, and (5) priced at not more than a small fraction of the cost for conventional fire control equipment. The capabilities for providing gunsights were based on adaptations of models already built earlier. The success of our concepts and equipment, designed and produced by the Sperry Gyroscope Company and associated contractors, was clearly demonstrated during many ship and aircraft encounters during World War II. This achievement brought the Laboratory, now renamed the INSTRUMENTATION LABORATORY, wide recognition. It also generated the background of ideas, cadres of people, and equipment necessary for assuming tasks in guidance based on inertial principles.

On the engineering side, the development of naval antiaircraft fire control systems and airborne equipment for fighters and bombers permitted us to create and reduce to practice several unconventional viewpoints toward dynamical theory. Later these viewpoints became key factors in designs for the basic components of inertial systems. A breif look at the principles applied is not only useful but essential for understanding the fundamental background in discussions of later developments. The theoretical background is based on Newton's Law of Inertia which states that the vector change in momentum of a mass with respect to inertial space is determined by the applied force, being in the direction of the force, proportional in magnitude to the magnitude of the force, and inversely proportional in magnitude to the magnitude of the mass involved; applied to rotational motion, this law becomes the statement that the time rate of change of angular momentum of a body with respect to inertial space is equal to the applied torque.

Students of mechanics are well aware that for bodies of generalized shapes with forces and torques arbitrarily applied, the mathematical expressions for the resulting motions are complex, and descriptions of behavior quite involved. Years of study had brought me considerable familiarity with the exhaustive treatments found in comprehensive textbooks. But practical experience had convinced me that, for engineering purposes, all the essential actions of sensing devices could be derived from theoretical assumptions of relatively simple mechanical arrangements. The basic ideas were elementary, and corresponded to design parameters that could be adapted to practical constructions by simplifying the six-degree-of-freedom circumstances of a body free in space in situations where essential actions could be effectively described by considering only one or two degrees of freedom. This implied designs of constraint systems for unbalanced masses or spinning rotors that restricted motions to conical angles with respect to a point or to simple angular displacements about a single axis of rotation.

Before the early 1940s, when the Laboratory developed antiaircraft gunsights for operation on the moving decks of surface vessels, the gyroscopic rotors commonly used in marine compasses and naval stabilization equipment were carried by arrangements having two degrees of rotational freedom. The suspensions employed elastic members and bearings designed to work with very small friction levels. It followed that, ideally, the supporting means caused negligibly small uncertainty torque components to act on the angular momentum associated with the spinning rotors. Under Newton's Law for Gyroscopic Action, this meant that, because "zero" torque was acting, the angular momentum vector did not change its direction with respect to inertial space, consequently, the spin axis exhibited the property of being "rigid in space." Instrument operation using gyroscopic rotors generally depended upon this action for stabilization to exclude effects of undesired base motions, while using changes in spin axis direction to produce control torque components for generating desired results. Two-degree-of-freedom gyro units, having suspensions without significant friction uncertainties, were said to have the basic property of "rigidity-in-space," while essential operation was associated with precession under torque components derived from control inputs within associated mechanisms.

All of the fire control developments at the Laboratory were based on single-degree-of-freedom gyro units instead of the two-degree-of-freedom type that was general for both marine and aircraft applications before 1940. The only instrument in common use before 1940 that employed the single-degree-of-freedom design feature was the so-called Rate-of-Turn Indicator for aircraft, that applied the ideas from patents of Professor Henderson. This device did not and was never intended to provide performance of quality suitable for navigation or guidance.

In the machine gun fire control equipment developed by the Laboratory, three single-degree-of-freedom gyro units were mounted on a rigid member with the spin axes of their rotors mutually orthogonal, and carried by single axis gimbals with directions of their rotational freedom at right angles to each other. Variable spring restraints about the gimbal axes were adjustable in stiffness as a function of range to the target. Viscous action of a thick fluid in the clearance between the gimbal and the case was used to provide protection against mechanical shock and vibration, while at the same time supplying drag torque to damp out the effects of roughness associated with gun shock and vibration. As the gunner moved his weapon, rotation of the member carrying the gyros caused the three gimbals to tip until the restraining springs developed restraining torques to balance the gyro output torques corresponding to components of input angular velocity.

These gimbal rotations were coupled mechanically to a system of mirrors whose angular deflections established on optical-reticle indicated line of sight offset behind the gun barrel. The gunner had only to keep moving the gun as necessary to maintain the reticle image on the target. The corresponding forced motion of the gunsight case generated lead angles that caused the gun to fire its projectiles ahead of the target by a proper angle to correct for target motion during bullet travel. With this arrangement, the fire control problem was effectively solved using inertial space, and it was unnecessary to mechanize any coordinate transformations. In effect, deck motions did not enter the problem, being eliminated by a gunner who kept the reticle on the target, so that they did not affect the fire control predictions.

In practice, this was not altogether true because human gunners were unable to accommodate perfectly for deck tilts and angular velocities to keep his optics exactly on the target, but the mechanization allowed inexperienced gunners to deliver effective anti-aircraft fire under combat conditions. Since the fire control problem did not need geometrical transformation devices, the gunsights were compact, being not much larger or heavier than standard typewriters, while they generated effective solutions rapidly enough to keep attacking aircraft in considerable danger while they remained within range of the guns. Though the fire control system designs were not important for the inertial navigation systems, they applied single-degree-of-freedom gyro units and provided an extensive and fundamental engineering and design background for the sensors that would be developed for Inertial Navigation Systems.

INERTIAL SENSOR PRINCIPLES: FUNDAMENTALS OF GYROSCOPIC THEORY

Aerospace guidance technology developed by the Laboratory depended upon engineering applications of Newton's Laws. These applications are difficult to interpret without a pattern of generalized theory to simplify concepts and clarify representations. A pattern of this kind is developed in Figures 1 through 6. Devices of two types are important for inertial systems; one type, called the specific force sensor, is required to be responsive for resultants formed by gravitational and inertial reaction forces which act on each particle of the materials involved. The other type, called the angular deviation sensor, receives angular deviations with respect to inertial space from arbitrarily established reference orientations. Sensors of the first type generate signals from which navigational information on acceleration, velocity, and location may be derived. Sensors of the second type supply signals that can be used as inputs to servo-drive systems for correcting deviations of specific force sensors from desired orientations.

Figure 1 is taken from an Instrumentation Laboratory publication of the 1940s showing the essential sensing element in a single-degree-of-freedom specific force receiver consisting of an unbalanced mass carried by a shaft, pivoted about an axis fixed to the instrument case. In practice, damping, output signal generation, torque restraint, and other functions have to be included as necessary services provided for the force-sensing mass in a complete instrument. Some of the various essential components that must be combined to give overall operation are labeled and named.

Gyroscopic actions associated with a rotor spinning at relatively high angular velocity about an axis of symmetry are generally regarded as less obvious than the apparently straightforward dynamic "lagging-behind" of a mass under linear acceleration. In fact, if vector representations are understood and used, smooth, high-speed rotation has the effect of one integration, and makes the behavior of a gyro constrained to single-degree-of-freedom operation even simpler than the interaction of a mass with linear acceleration. Figure 2 is a summary of the definitions, conventions, and representations used to associate gyro rotors with vectors and torques. Figure 3 is a pictorial representation of a gyro rotor and gimbal mounted with two degrees of angular freedom on

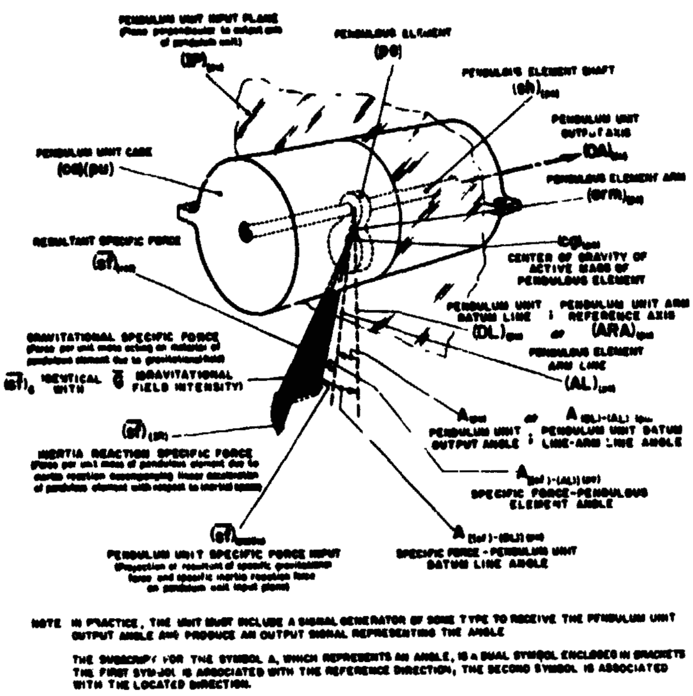

Fig. 1
Line Schematic Diagram Showing Single-Degree-of-Freedom Pendulum Unit as an Orientational Signal Receiver for the Direction of Specific Force Projected on an Input Plane

a base. With the spin axis substantially horizontal, a force applied to the inner gimbal about the axis at right angles to the gimbal axis produces a torque vector at right angles to the angular momentum vector. By Newton's Law of Gyroscopic Action, the response of the rotor is to turn its spin axis toward the torque axis in the angular motion called precession. The direction of change of position always tends to shift the arrowhead of the moving vector so that it points in the same direction as that of the torque vector. The diagram of Figure 3 is, of course, greatly simplified, in single-degree-of-freedom gyro units for use as angular deviation sensors in guidance systems.

Figure 4 summarizes the engineering definitions made in treating spinning rotors as gyroscopic elements, and the theoretical consequences that follow these assumptions. By definition, a gyroscopic element includes the following three features: (1) a rotor spinning about an axis of symmetry, (2) the spin angular velocity is constant in magnitude, and (3) angular velocity magnitudes about axes other than the spin axis never exceed insignificant levels, and moments of inertia about axes at right angles to the spin axis are all so small that the angular momentum of the system is effectively concentrated in the rotor along the spin axis.

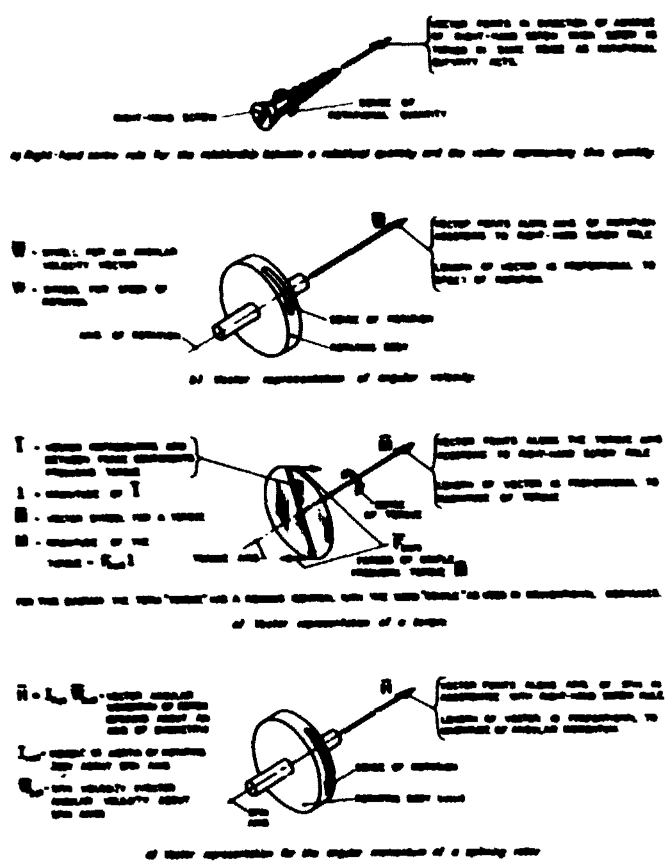

Fig. 2
Vector Representation of Rotational Quantities

Under these assumptions, the equation of motion for a gyroscopic element reduces to the statement that the applied torque is equal to the cross product of the angular velocity of the spin axis with respect to inertial space and the angular momentum vector. In other words, the angular momentum vector has an angular velocity of precession that turns it toward the torque vector. The output torque from the gimbal when an angular velocity with respect to inertial space is imposed on the angular momentum vector, is given by reversing the order of terms in the cross product. Figure 5 illustrates an arrangement with a gyroscopic element incorporated in an instrument case as the sensitive element of a basically single-degree-of-freedom angular deviation receiver. The vector component performance equations are written down for a generalized orientation of the gyro element and its gimbal within the case. In engineering practice, all the angles between axes fixed to the structure carrying the rotor and the enclosing case remain very small, so that small angle assumptions in theory are all valid for all deviations as they are shown.. Figure 6 is a line schematic diagram, with definitions and symbols, showing a gyro

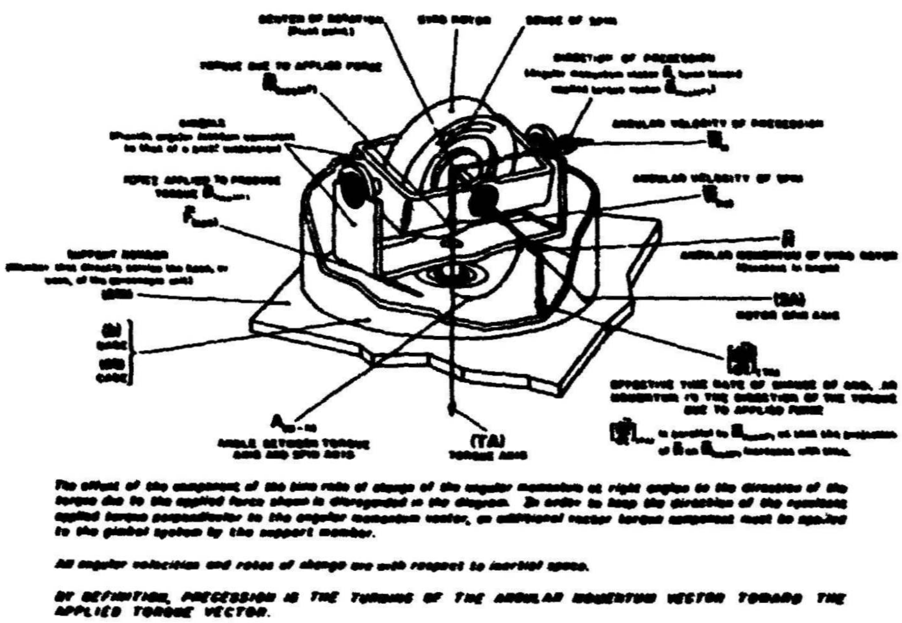

Fig. 3
Pictorial Schematic Diagram of Gyroscopic Unit Model Illustrating the Precession of a Gyroscopic Element Due to an Applied Torque Acting About a Fixed Axis

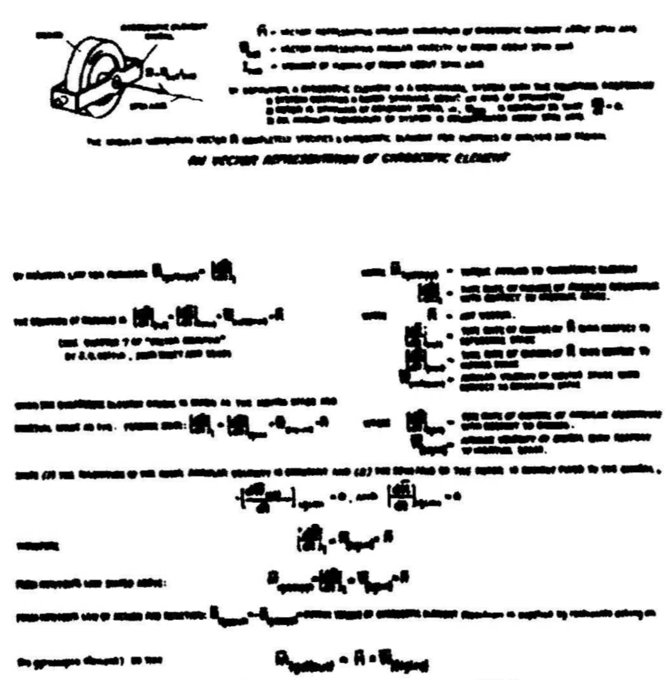

Fig. 4
Vector Representation and Basic Performance Equation for the Gyroscopic Element

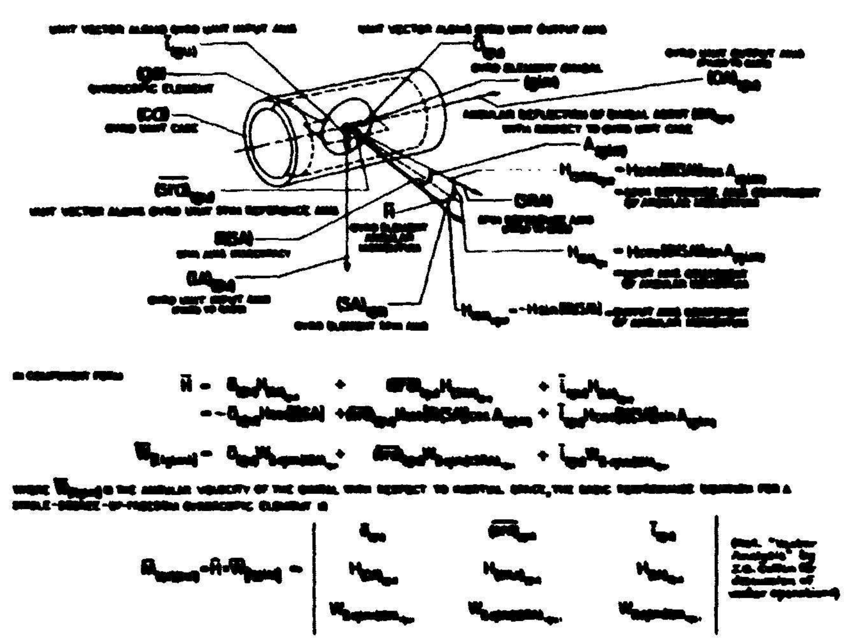

Fig. 5
Coordinate Diagram and Static Performance Characteristic for Single-Degree-of-Freedom Gyro Unit with Non-Ideal Geometry

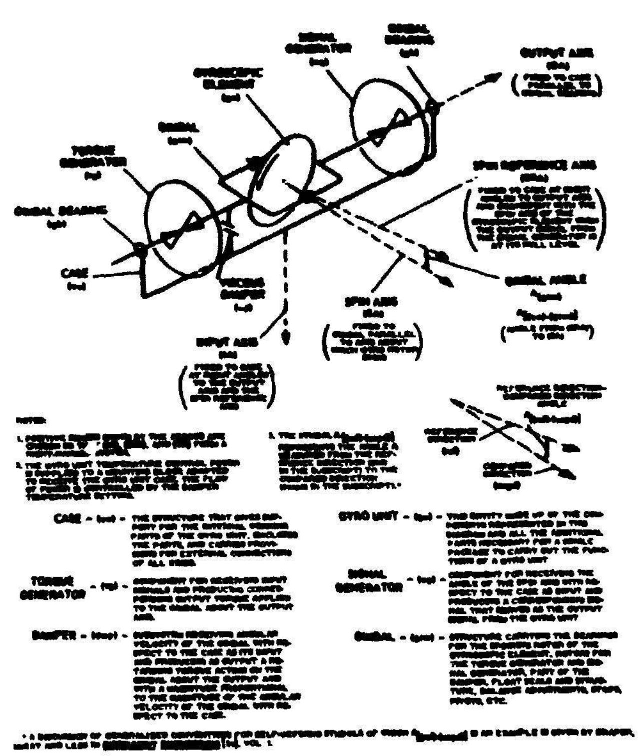

Fig. 6
Line Schematic Diagram for the Single-Axis Integrating Gyro Unit (Single-Degree-of-Freedom Angular Deviation and Command Signal Receiver)

element combined with the other functional components needed to form the fundamentals of a single-degree-of-freedom angular deviation receiver that is adequate for engineering discussion, design and test purposes.

The combination of concepts and components defined and represented in simple form by the line schematic diagram of Figure 6 forms the basis for all the single-degree-of-freedom integrating gyro units created and pioneered during the 1940s by the Instrumentation Laboratory. Angular deviation sensors based upon the features summarized in Figure 6 have been manufactured in large numbers and successfully applied in many aircraft, spacecraft and marine systems. Sensors of the type illustrated derive their name from the fact that rotation of the case about the input axis can only occur if a torque exists which, imposed upon the rotor, causes the angular momentum vector to turn toward the torque vector about the output axis. This turning is resisted by a viscous drag torque in the damping fluid which is proportional to the angular velocity of the damper within the case. Since this torque is proportional to the "output" angular velocity of the gimbal about the gimbal axis, which in turn depends on the gyroscopic torque produced by the "input" angular velocity, the overall action is one of integration. The electrical output from the signal generator measuring the rotation of the gimbal within the case, for this reason gives a direct indication of rotation for the case with respect to inertial space about the input axis. Many refinements and complexities beyond the elements suggested in Figure 6 are necessary before working sensors can be realized, but the fundamental ideas involved are described by the diagrams. Because the basic gyroscopic input is case angular velocity about the input axis, while the unit output is an electrical signal representing the integral of this input, instruments with the features represented in Figure 6 are called Single-Degree-of-Freedom Integrating Gyro Units, or more usually, IRIG's (Inertial Reference Integrating Gyros).

STATE OF INERTIAL EQUIPMENT ART IN THE LATE 1940s

At the end of 1945, changed circumstances made it possible for the Instrumentation Laboratory to actively attack the problem of inertial control, navigation, and guidance for aircraft. At that time the only effective devices that used inertial and gravitational effects associated with the Earth were the marine gyro compass and the stable unit used for fire control reference purposes. The rotors in these instruments all had two degrees of freedom and weighed many pounds. The complete equipments stood some four feet high with horizontal dimensions approximating one foot. Many engineers believed that large, rapidly spinning wheels were the only means for sensing the Earth's rotation and detecting deviations from reference orientations small enough to provide practical stabilization. In common with all government sponsors of new projects, the Air Force wanted to make use of existing technology for airborne inertial systems.

Following this plan of attack, the Laboratory installed and flight tested an ARMA Stable Vertical Model (commonly applied in the U.S. Navy for fire control purposes) in an Air Force DC-2. The equipment was large and heavy. Without outside reference, vertical indication performance was not good enough for airborne navigation and guidance aimed at errors less than one mile at the end of a ten-hour flight period. It has already been noted that the aircraft Bank and Climb Indicator and the Turn Indicator had performance limitations with the order of a few degrees which, in the 1940s (and for all later times), qualified them for stabilization service but not for navigation or guidance. At the beginnings of the Instrumentation Laboratory's work on inertial navigation and guidance, we concluded that new mechanization would have to be developed from fundamental principals without dependence on anything available from existing technology.

FUNDAMENTAL MECHANIZATION REQUIREMENTS FOR CONTROL, NAVIGATION, AND GUIDANCE SYSTEMS

Achieving practical results without undue concern for the disciplines in science and engineering became my early pattern of action at M.I.T. Following this approach, the Instrumentation Laboratory became a laboratory of pioneering technology. Thus, the technology represented by the 1946 Air Force Project involved searching out all the necessary inputs and generating the control and guidance commands needed to stabilize aircraft motions and determine flight paths. We clearly recognized that the overall processes had to deal with the quantities of generalized six dimensional geometry, and that self-contained systems for the sub-function of navigation could not depend upon continuous radiation contacts with known points of the Earth. This meant furnishing, on-board, coordinates stabilized against erratic and systematic aircraft rotations, suitably arranged to maintain the input axis of specific force sensors so that all possible resultants of gravitational forces and linear accelerations were completely accepted.

Flight tests of gyroscopic units used for marine applications had clearly demonstrated that such equipment was not only deficient in performance, but had sizes and weights beyond those allowable for aircraft. To overcome these objections, we decided on design studies to minimize the weight and bulk of gyro rotors and their supporting gimbals, and to reduce levels of undesired torque acting to cause erratic angular deviations of the active angular momentum vector. This meant abandoning the concept of a heavy rotor--holding its spin axis direction in the presence of torque by sheer inherent power of spinning mass--for a mechanization where gyro units, using relatively small rotors carefully isolated from undesired torque components, acted to operate signal generators requiring substantially zero torque with outputs representing angular deviations. In

1945, the relatively new technology of servomechanisms was perceived as the key to converting gyro deviation signals into torque components for maintaining geometrical members in reference orientations substantially free of interference by supporting base motions.

Thus, without concern for details of design, the functions needed to implement geometrical reference functions were recognized as:

1) One or more mechanical reference members with a total of three degrees of angular freedom with respect to the supporting aircraft.

2) Angular deviation sensors to detect orientational changes of the reference member from desired reference positions and to generate corresponding output signals.

   a) Two two-degree-of-freedom angular deviation sensors.

   b) Three single-degree-of-freedom angular deviation sensors.

3) Servodrive systems to accept the angular deviation sensor signals and apply torque components to the geometrical reference member supports as required to overcome the friction, unbalance, and other torque components tending to disturb the geometrical member orientations from desired reference positions.

4) Means incorporated in the gyro units to sense angular deviations for supplying servodrive inputs to cause changes of the geometrical reference member orientations in response to command inputs.

5) Angle sensors to provide signals representing aircraft orientation with respect to the geometrical reference member.

6) Specific Force Sensors with their input axes properly related to known directions in the geometrical reference member so that the output signals representing components along their input axes could be combined to provide complete information on the resultant specific force input.

7) Electronic components as necessary to service stabilization drives and sensors.

8) Computing systems:

   a) To receive signals representing orientation of the geometrical reference member with respect to Earth or directions determined by celestial bodies and generate orientational change commands for the reference member.

   b) To receive signals from the specific force sensors, correct out gravitational effects and generate indications of location and velocity with respect to the Earth.

   c) To compare indicated locations and velocities with respect to programmed states of these quantities in terms of Earth or other chosen external spaces, and from this comparison to determine the corrections to vehicle motion needed to achieve final mission success.

   d) To generate command signals to serve as guidance system outputs representing these corrections and to serve as the essential inputs for the control system which provides interface functions to couple the guidance system with the vehicle and its driving system.

9) Various readouts, indicators, monitoring arrangements, mode-of-operation selectors, manual controls, etc., to meet the requirements of particular situations.

Even a brief discussion of the subjects suggested in this far-from-detailed listing is impossible within the scope of this paper. There is surely no reason to review here, the theory, mathematics, and practice of the ancient art of navigation available in 1946. Similarly, the computer functions required and state-of-the-art components available for use in new equipment were well known. So much effort elsewhere was being devoted toward progress that the Instrumentation Laboratory found no valid excuse for adding any new workers to the fields of computer technology. Considerations of the same kind led the Laboratory away from tasks associated with readout arrangements and indicators. It appeared that the area where the Laboratory could make truly significant contributions included sensors for inertial quantities, and mechanizations associated with the realization of geometrical reference members to achieve the objective of an error build-up of one mile in ten hours flight by a self-contained guidance system. Knowing that all the fundamental components had to be conceived, designed, built and tested, this was the goal the Laboratory began to work toward in 1946.

GEOMETRICAL REFERENCE MEMBER MECHANIZATION: PRINCIPLES

Inertial system work in the Laboratory started with design studies following the general two-degree-of-freedom gimbal suspension pattern that was commonly found in gyroscopic equipment for marine purposes. Among other features, we were particularly interested in the technique of rotating a part of the gimbal structure about the indicated vertical axis to reduce friction effects by periodically reversing the direction of undesired torque components with respect to the angular momentum of the gyroscopic rotor. So many detailed considerations became involved as designs were worked out that I can do more than suggest a few of the obvious decisions that started new paths of development for inertial systems in 1946. Figure 7, complex as it may appear, is a simplified diagram of an arrangement of elements that was studied on paper and, to some extent, in working hardware directed toward realizing the functions of a stabilized member.

Two, two-degree-of-freedom gyro rotors were mounted within double gimbal systems which in turn were carried on the structure of a stable member that was mounted with pitch, roll, and azimuth freedom in gimbals carried by the airplane framework. Each of the two gimbals for each rotor carried an electrical torque motor. In combination, the motors were arranged so that their outputs could precess the spin axes to any desired orientations with respect to selected reference directions. The gimbals carrying the stable unit were equipped with torque motors having outputs sufficient to overcome friction and inertia effects associated with the support bearings. Each of the torque motors was part of an assembly including a "pick-off" to generate electrical signals representing angular deviations about the various axes. The pick-offs and torque motors were combined in servo-drive loops with suitable electronic power amplifiers so that signals from the gyro units could accurately determine the orientation of the stable unit without imposing disturbing

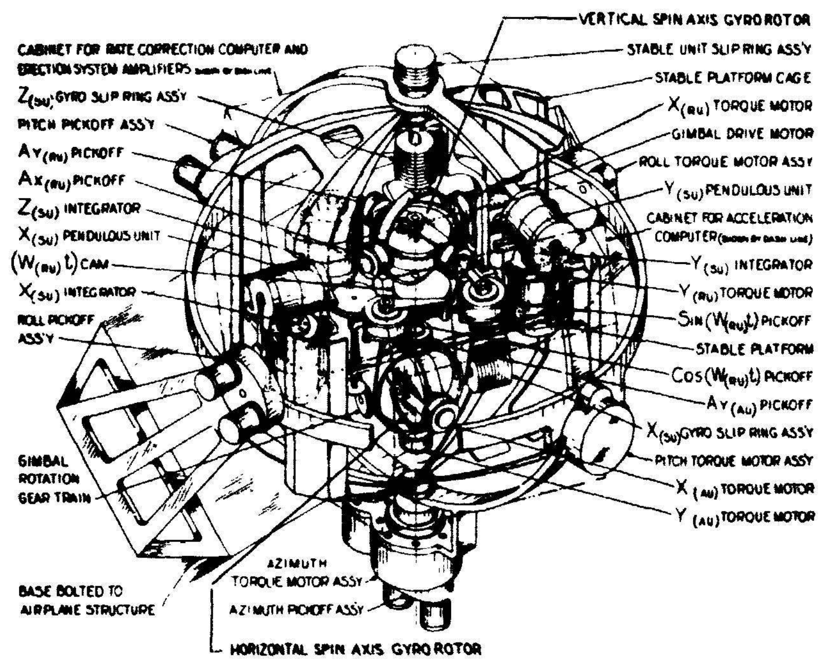

Fig. 7
Two-Degree-of-Freedom Gyro Stabilization Unit

torques on the gyro rotors. This application of servo-mechanism technology—to control orientation of relatively heavy members, with reference directions established by gyro unit gimbals without imposing any significant torque on the rotor has been universally adopted by designers of inertial guidance equipment.

Two single-degree-of-freedom pendulum units provided the specific force receiving functions for the arrangement of Figure 7, with torquing and signal generating functions performed by components within the units supporting the axes of the two pendulums. Components to integrate the gyro torque motor input currents and determine the changes in spin axis orientation appear as integral parts of the system. Computing functions are suggested as system parts in Figure 7 by a dashed line indication of a cabinet. The computations to be performed could have been carried out by using a variety of detailed arrangements, but vehicle location, velocity, and motion corrections both as indications and also in terms of control commands were results required from any system.

We found that well-qualified mathematicians could design adequate computers which could be implemented by the technology available. But the instrumentation for realizing complete and accurate geometrical information with on-board equipment suitable for which solutions had to be found. For these reasons a year's work on inertial guidance reaffirmed our earlier decision to concentrate on inertial sensors and the technology of generating and applying geometrical information by self-contained onboard systems.

We chose a reference member stabilized and constrained to follow the direction of the local vertical as the carrying aircraft moved over the Earth's surface. This member provided a basic input from which self-contained equipment could derive navigational indications. Of course, it would be necessary to compensate for the effects of acceleration on the outputs from the sensors in order to achieve accurate indications of the vertical. Directions on the Earth's surface (the heading from North for example) would also be needed. Finally, some geometrical reference for measuring with good accuracy the angular motion of the local vertical was needed to determine distances covered on the Earth's surface. Inertial space could be used as this reference by relating the integrals of torquing inputs applied to the gyro rotors to angles of spin axis rotation by calibrations of the sensors. Another approach involved including a physical member that would hold a selected and established reference orientation with respect to inertial space as part of the overall system. Changes in local vertical directions corresponding to travel over the Earth could be read out in terms of angular displacements with respect to this reference member. By 1951 both of these approaches to the orientational reference problem had been implemented in designs of test models built in the Instrumentation Laboratory.

STABLE VERTICAL BASED ON THREE SINGLE-DEGREE-OF-FREEDOM GYRO UNITS AND TWO SINGLE-DEGREE-OF-FREEDOM PENDULUM UNITS

Reviews of past experiences with aircraft instruments, gunsights, marine equipments, and experiments with specially designed test devices, showed that friction levels obtainable from ball bearings could not be reduced below the order of ten dyne centimeters. Gyro rotors of reasonable weight, a few hundred grams, spinning with angular velocities of several tens of thousands of revolutions per minute provide angular momentum with magnitudes not far from one million gram centimeters squared per second. The corresponding precessional rate for a ten dyne centimeter disturbing torque is 10^{-5} radians per second. Earth's rate is fifteen degrees per hour which is about 7.3×10^{-5} radians per second. It thus appeared that there was no hope of using ball bearing supported gimbals to achieve drift rates that were less than several times Earth's rate with gyro rotors of reasonable size. At fifteen degrees per hour, where each degree corresponds to sixty miles of distance on the Earth's surface, it would be impossible to achieve stability in geometrical reference member orientations permitting navigational uncertainties less than several miles. This led us to conclude that gyro gimbal supports for practical inertial navigation systems could not be realized with ball bearings.

Many possibilities, elastic members after the pattern used for the gunsights, electromagnetic fields, electrostatic fields, hydrostatic pressurized bearings, grease bearings, "squeeze" film bearings, and various other schemes were tried and abandoned for one reason or another. After a number of researches to determine the integrational accuracy that could be achieved by shear drag forces generated from velocity gradients in thin layers of viscous fluids, we decided to use floatation for providing most of the support for a single gimbal structure designed as a hollow float to directly carry gyro rotors and their spin axis mechanisms for single-degree-of-freedom configurations. By adjustment and continuous control of temperatures, floatation forces could account for support of all but a small fraction of one percent of the gimbal weight. As a useful by-product of this arrangement, viscous drag integration of gyro output torque about the gimbal axis could lead to signals representing case rotation about the input axis so that the overall gyro unit would provide angular deviation output signals. In practice, the addition of means for magnetic support without disturbing torque could make it possible to absorb residual non-floated weight and realize gyro units with gimbal output axis friction reduced below one thousandth of a dyne centimeter. These considerations for gyro units were found to apply with equal validity to pendulums and sensors of various types to receive specific force. The same design features were found to be effective remedies for various other difficulties involved.

Engineering studies showed that, except for very short transient periods of alignment, reference directions fixed to the structure of the stable member had to be servo-controlled within small angular deviations from reference directions determined by the gyro spin axes. This made it possible to eliminate one gimbal from each gyro rotor suspension in an arrangement with the features illustrated in Figure 7, and to use single axis signal pickoffs for the remaining single axis gimbals. Pickoffs of this kind working about a single axis needed only a very limited range, on the order of arc seconds, of angular motion to accommodate for any deviation that normally operating servo-loops would ever allow to occur in stable member orientation. Realization of this fact determined the essential pattern of sensor design, and made it possible to use the simplest possible engineering features in construction.

Figure 8 is a 1946 artist's representation of a three-degree-of-freedom-servomotor-powered gimbal arrangement supporting a stable platform. This platform carried three single-degree-of-freedom gyro units with their input axes mutually at right angles to sense angular deviations with respect to inertial space about these three directions. Two single-degree-of-freedom units with external pendulums are shown with their pivot directions fixed to the stable platform. Although details of construction are suggested rather than shown here, the general arrangement of functional components proved so satisfactory that we used it directly or with suitable modifications in many inertial guidance systems designed in later years by the Instrumentation Laboratory.

Figure 9 represents the configuration shown in Figure 8 in a line schematic diagram for a complex of components to operate as the basic mechanical subsystem of the stable vertical. The essential operational relationships, including electrical quantities

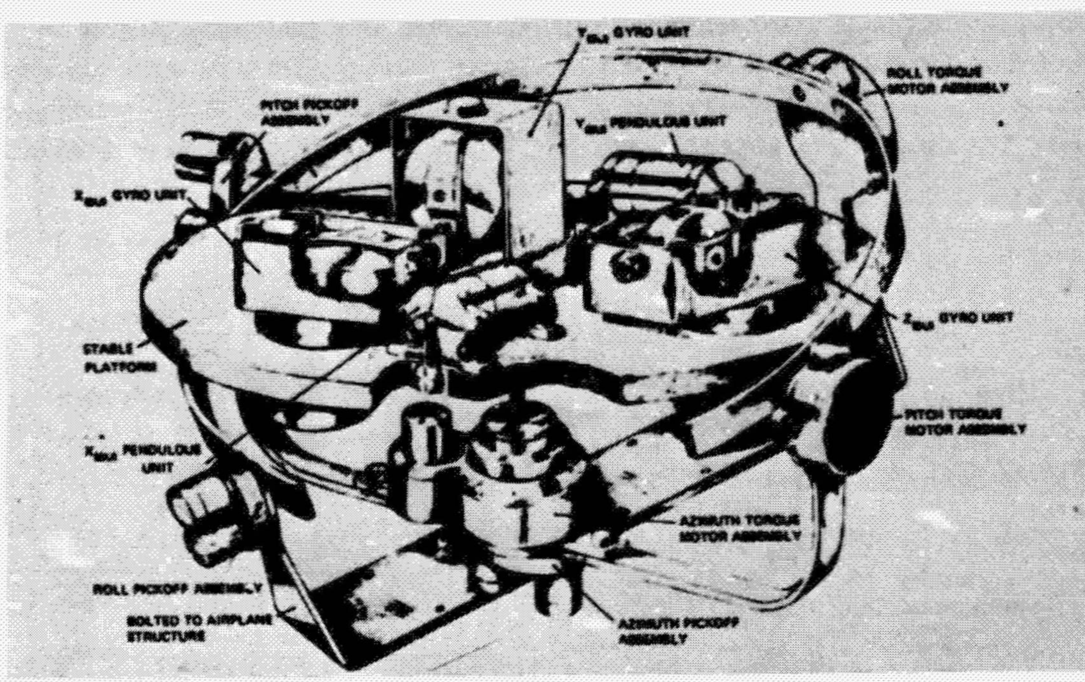

Fig. 8
Single-Degree-of-Freedom Gyro Stable Platform

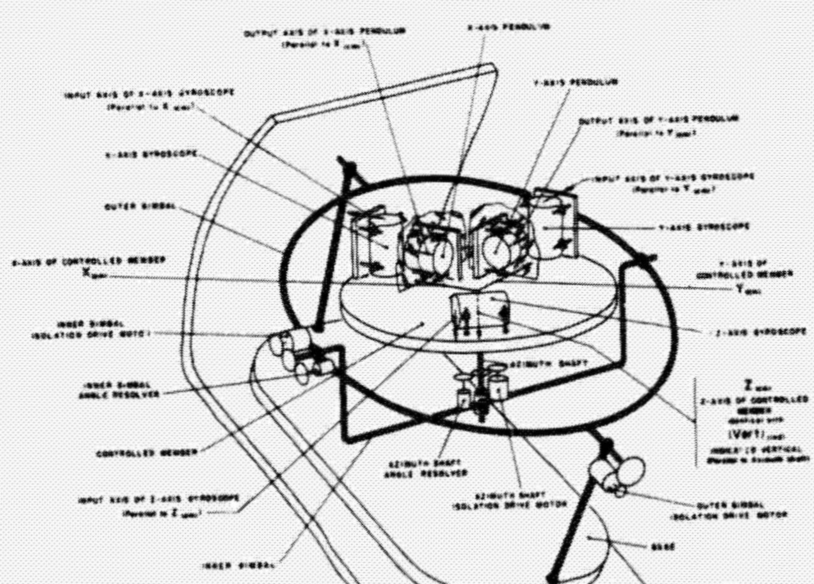

Fig. 9
Essential Components of the Stable Vertical

processed by amplifiers and computers, are represented in a functional diagram in Figure 10. A detailed explanation of this diagram would require more words and space than are available here. If an impression of the nature and complexity of the relationships involved is suggested by Figure 10, the writier's objective will have been achieved.

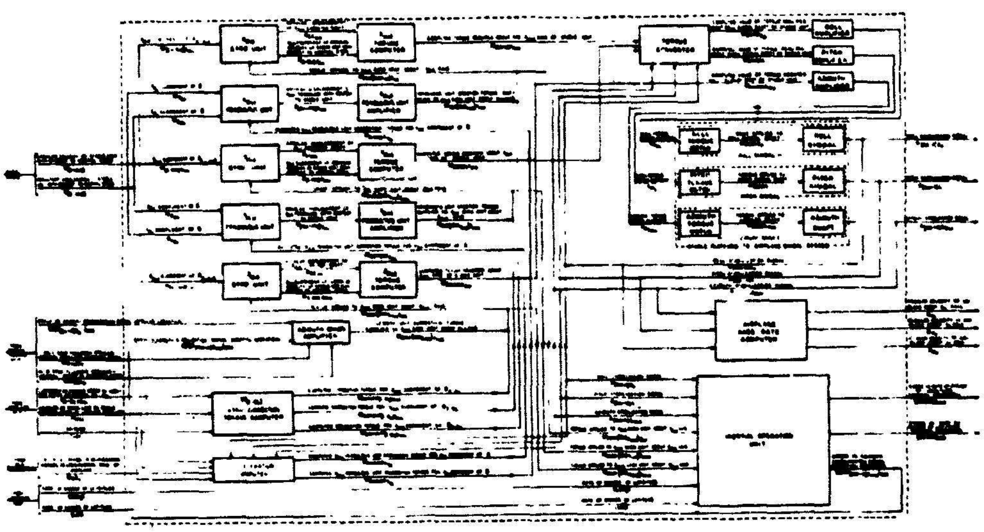

Fig. 10
Functional Block Diagram of Single-Degree-of-Freedom Gyro Stabilization Unit
(Flow of Information Only)

PRACTICAL SINGLE-DEGREE-OF-FREEDOM INERTIAL SENSORS

Single-degree-of-freedom sensors for angular deviations and gravity have been shown in the mechanical subsystem diagrams of Figures 8 and 9. In Figure 8 both units and pendulums are represented as having journal bearings without any remarkable features. Figure 11 is an artist's rendition of the arrangement used in the first experimental pendulum unit. Ball bearings fitted in the instrument case were used at each end of the shaft which carried the pendulum. Salient pole stators mated to direct drive rotors fixed to the shaft, served the functions of generating output signals and applying command torques to the pendulum. An aluminum cylindrical cup mounted on the shaft and rotating in the field of a permanent magnet provided damping for pendulum rotation.

Tests of engineering models incorporating the features shown in Figure 11, and including ball bearing supports for the output shaft, gave angular position uncertainties much larger than the fractional arc minute required for inertial guidance specific force receivers. Studies of all the principles that might overcome this and other difficulties

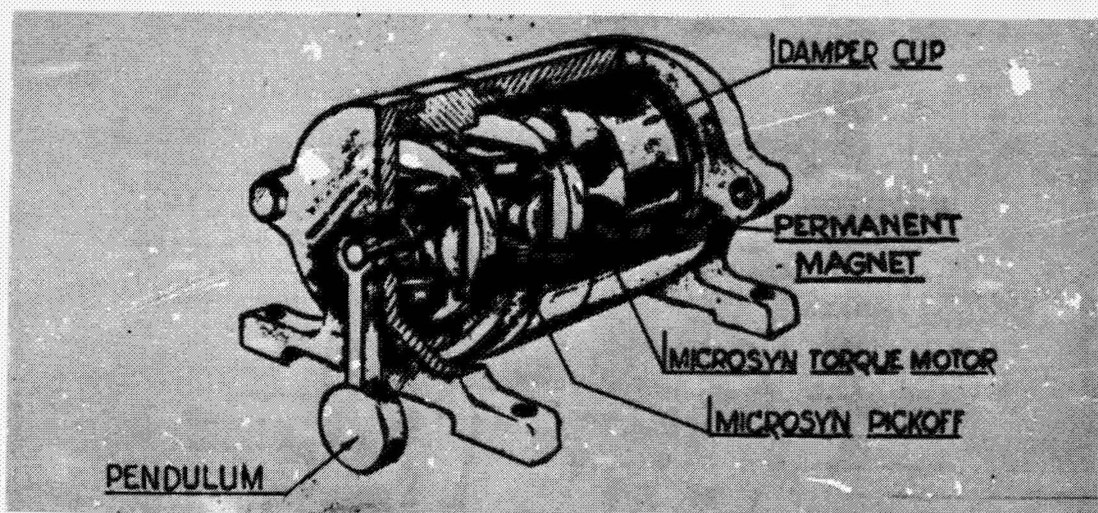

Fig. 11
Pendulous Unit

led to the choice of floatation support supplemented by polished watch-type pivots and jewels. The general principles applied in the configuration chosen for pendulum unit design are illustrated in Figure 12. The pendulous element was enclosed in a sealed cylindrical chamber weight adjusted to just float in the viscous fluid filling the clearance volume between the cylinder and the case. This depended upon maintaining temperature at the proper level. Figure 13 is a sectioned drawing showing the details of construction for an actual single-degree-of-freedom pendulum unit. Units of this kind were used in the systems that are described later in this paper.

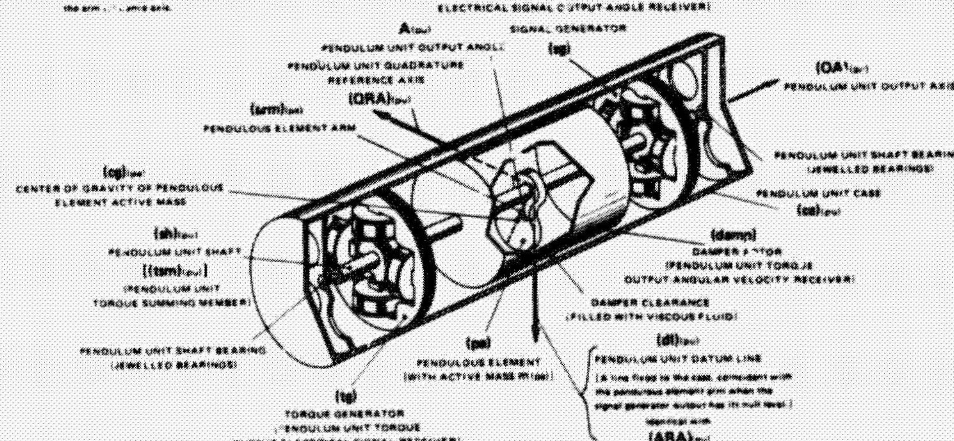

Fig. 12
Pictorial Schematic Diagram of Damped Single-Degree-of-Freedom Pendulum Unit

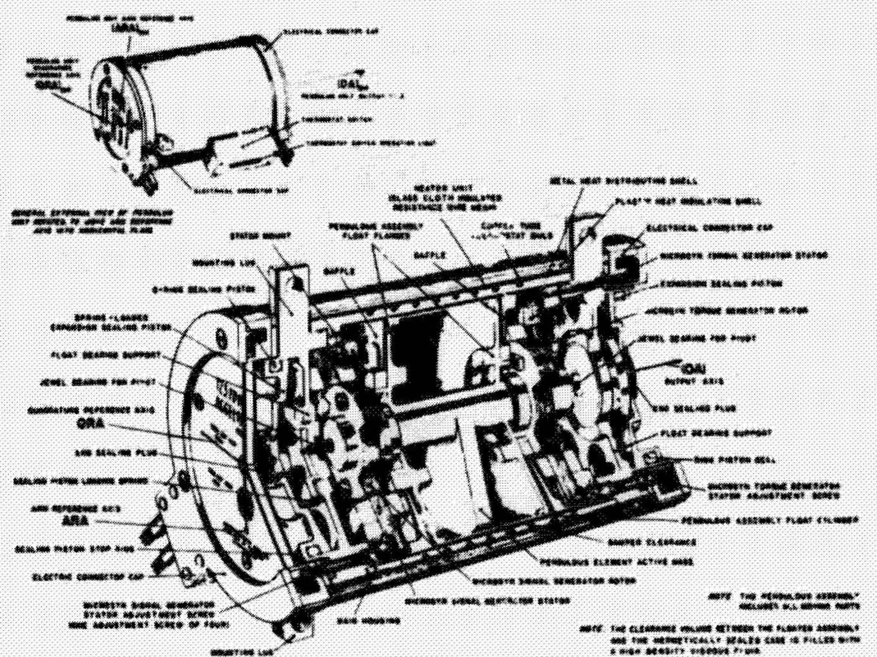

Fig. 13
Sectioned View Showing Constructional Details of
Single-Degree-of-Freedom Pendulum Unit

Gyro units built with ball bearing gimbals gave entirely inadequate engineering test results. Inaccuracies could definitely be traced to erratic and excessively high minimum torque levels and to susceptibility to torque disturbances under vibration and mechanical shock. Improvements great enough to achieve satisfactory gyro units were made by applying the same principles of floatation and viscous shear damping used in single-degree-of-freedom pendulum units with the features represented in Figure 12. Figure 14 is a corresponding diagram for the floating single-degree-of-freedom gyro unit. The gimbal carrying the spin axis bearings (which were ball bearings in all early units) was sealed in a cylinder from which shafts projected on both ends. The cylinder was adjusted in size and weight to float when the clearance between the cylinder and the case was filled with fluid maintained at operating temperature by means not shown in the diagram. Nuts accessible from outside the case were attached to the float by screws. Adjustment of these nuts in and out along the screws made it possible to realize a very close balance of the moving assembly. This assembly was free to rotate about polished pivots working within watch-type jewels mounted in the case. With almost-perfect floatation accompanying good thermal control, the small loads carried by the jewels reduced uncertainty torque effects sufficiently to achieve performance high enough to demonstrate the feasibility of test systems.

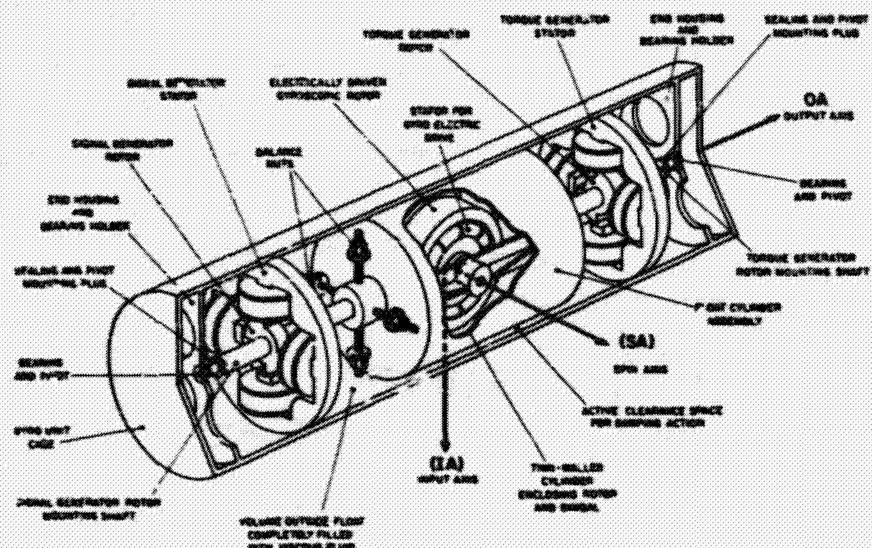

Fig. 14
Pictorial Schematic Diagram of Single-Degree-of-Freedom Integrating Gyro Unit

Alternating current electrical power for the gyro rotor was supplied to the float by flexible leads not shown in Figure 14. This figure shows a signal generator providing signal output from the unit representing the angular deviation about the output axis of the spin axis from its reference position (the direction, fixed in the case, along which the spin axis is aligned when the signal output has its null level). It also shows a torque generator that acted about the gyro output axis to cause the spin axis deviations from the reference alignment. A gyro unit output signal became the input causing the associated servomotor and stable unit structure (when the unit is mounted on a working platform) to rotate. This rotation had the direction of the gyro unit input axis to drive the spin axis toward its null signal orientation. Thus, command signals supplied to the torque motor of a gyro in the complete system caused the stable unit to rotate at a rate and in the direction determined by these signals.

Figure 15, which corresponds to Figure 13 for the pendulum unit, shows a cutaway of the design details of an actual single-degree-of-freedom gyro unit as this sensor was applied in the first inertial guidance systems designed and built at the Instrumentation Laboratory.

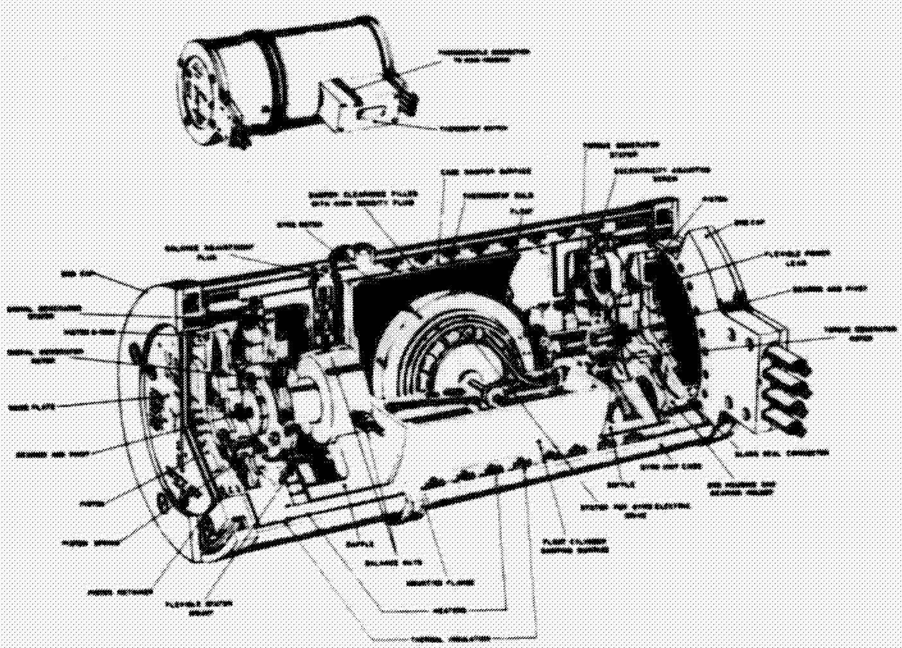

Fig. 15
Cutaway View of 1.5 F.G.-2 Integrating Gyro Unit

FIRST SYSTEM USING INERTIAL PRINCIPLES DESIGNED AND BUILT BY THE INSTRUMENTATION LABORATORY: THE FEBE SYSTEM

Starting in 1946, with no background in technology or any applicable flight experience, the Instrumentation Laboratory directed its efforts toward designing, building, and flight testing equipment that would demonstrate the feasibility of inertial guidance systems, and defining the directions that should be followed by engineering efforts. The Air Force assigned a B-29 aircraft to this task, but we lacked special ground equipment or even maps from which more than a few accurately known check points could be taken. Studies of the overall inertial guidance problem led to the choice of a local vertical indicating platform following the arrangements of Figures 9 and 10. This left the problem of azimuth determination open for the purposes of directional control of the aircraft, and also for navigational indications. Magnetic compass readouts were not suitable because of inherent inaccuracies and unavoidable oscillations or filtering time lags. For these reasons we decided to incorporate an automatic tracker for celestial bodies in the first system. Without adequate radio or radar ground equipment to continuously give aircraft position at night, the celestial body chosen for reference purposes was the sun. This permitted daylight operation and the use of photography for determination of position.

The name chosen for the experimental system was thus PHOEBUS, for the Greek God of the Sun, a name that was soon shortened to FEBE as the official name.

From the standpoint of mechanization, a gimbaled servo-driven tracking member carried an automatic optical tracker for following the line of sight to the sun by means of specially designed elements. Angles of the tracking member with respect to its supporting base, which was fixed to the airplane structure, were read out, and the corresponding signals transmitted to the computing system for use in forming control command signals and navigational locations. These indications, displayed to the human pilot, supplied the information necessary for steering the aircraft. Control command signals generated by the computer were also linked with the automatic pilot so that the Stellar-Inertial Guidance System could keep the aircraft on proper course to its target without attention from human members of the crew. Figure 16 is a side view diagram of the FEBE system installed in the rear compartment of a B-29 aircraft. Figure 17 is the corresponding diagram for the experimental equipment as seen from above. The various components and subsystems are labeled with the names defined in preceding figures of this paper. Figure 18 is a photograph from forward and above within the airplane, showing the actual FEBE installation. The complete system involved a bulk of some 4,000 pounds on the weight and balance chart for the airplane.

A number of test flights were made between Hanscom Field near Boston, Massachusetts, and various airfields in the midwest. Performance involving an error build-up of about ten miles for five hours flying time was achieved on a number of trips from east to west. Results of this kind certainly did not prove that our objectives for

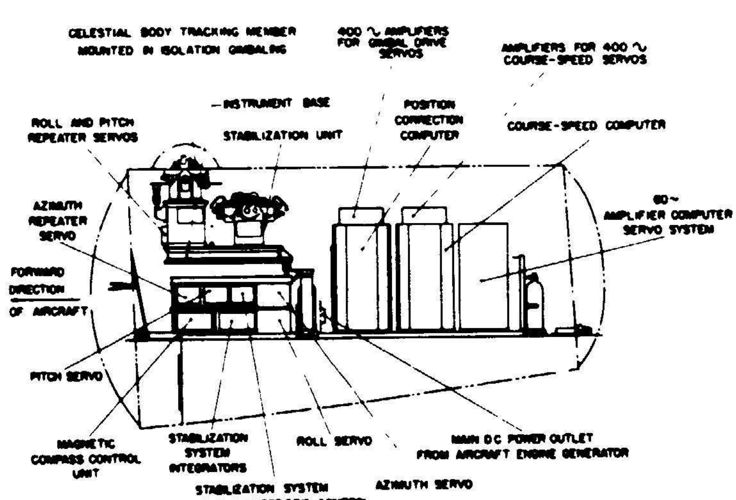

Fig. 16
Installation of FEBE System in B-29 Aft Pressurized Compartment Elevation View

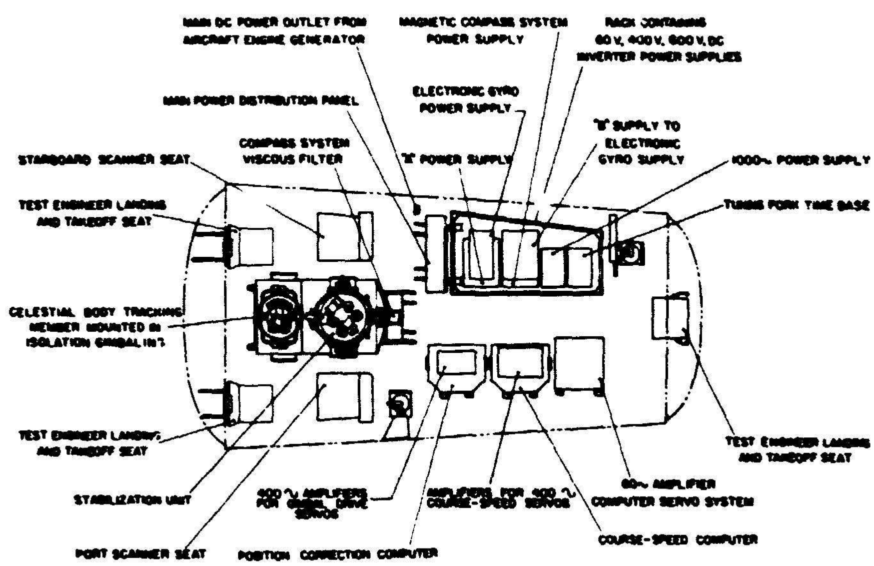

Fig. 17
Installation of FEBE System in B-29 Aft Pressurized Compartment Plan View

the project were attained, but they did give strong indication that guidance systems using inertial-only principles could be designed and reduced to practical operation.

By the end of 1949 it appeared that substantially all of the useful information from the FEBE system had been obtained, so engineering tests were stopped and work began on a second approximation of inertial guidance equipment, this time entirely free from dependence upon tracking of any celestial body.

THE SPIRE SYSTEM

Gyro unit and servodriven stable member behavior had been generally encouraging in the FEBE system, with drift rates in the fractional meru (by meru is one one thousandth of the Earth's rate, i.e., $10^{-3} \times 15°/\text{hour}$ which is approximately one minute of arc per hour) range achieved on numerous occasions. Several features of the experimental sensors could be improved by reasonable engineering changes, and there was strong optimism that all-inertial guidance systems could be built with smaller size, less weight, and higher performance than the FEBE system.

After preliminary studies were completed by the Instrumentation Laboratory, the Air Force sponsored a new inertial-only system, called SPIRE (Space Inertial Reference Equipment). The performance goal for SPIRE was a one or two-mile error build-up during ten hours of flying time. A geometrical reference member carrying three single-degree-of-freedom gyro units with input axes mutually at right angles, supported by servo-driven

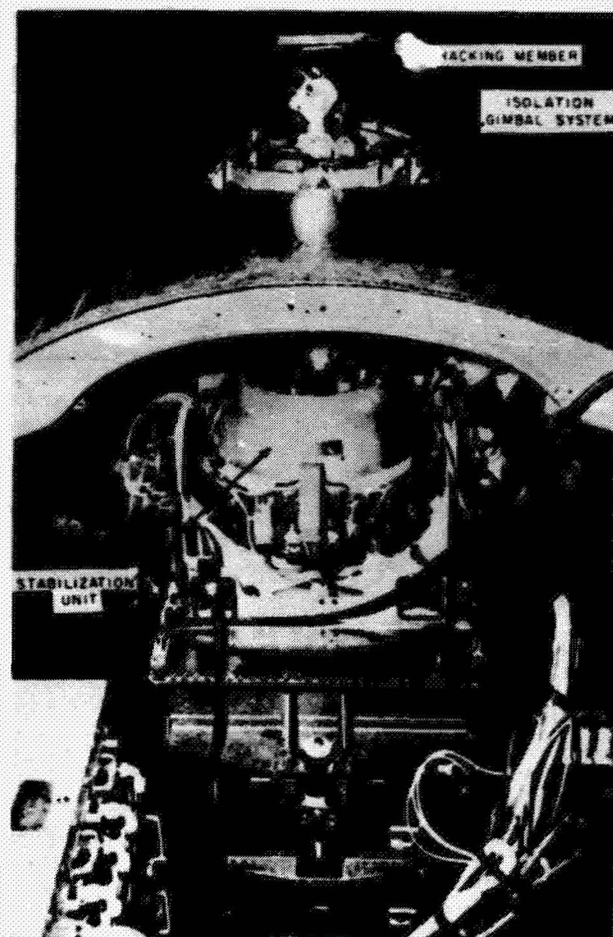

Fig. 18
FEBE System - Installation Showing Stabilization Uni
and Celestial Body Tracking Member

gimbals, allowed SPIRE to maintain a set orientation with respect to inertial space. The orientation chosen for the inertial reference package placed its polar axis along the axis of rotation of the earth. Two gyro units with their input axes at right angles to this polar axis maintained this direction with respect to inertial space. A third gyro unit with its input axis along the polar axis maintained the gyro package non-rotating with respect to inertial space. A drive, powered by an accurately-controlled-frequency source, was designed in to work about the polar axis between the gyro package and next outer supporting gimbal. Rotating this drive at exactly the Earth's rate caused the so-called line of nodes gimbal to remain alligned with the Earth as it rotated in space. The arrangement of the inertial package and its four supporting gimbals is shown in Figure 19.

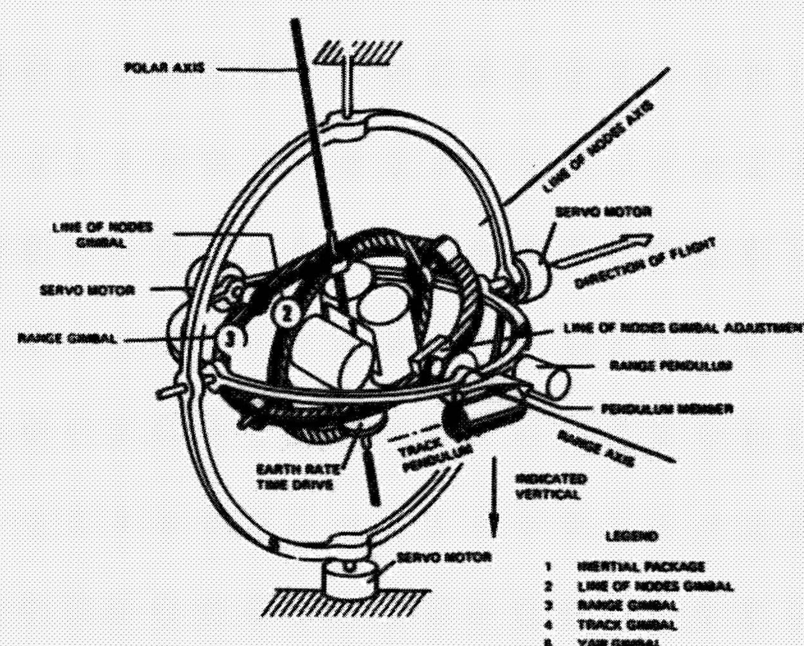

Fig. 19
Track Control

The operating principles of SPIRE allowed us to (1) use the inertial package and Earth rotation time drive to maintain the line of nodes gimbal in alignment with some arbitrary meridian on the Earth's surface, (2) apply two pendulums to sense the local vertical direction in the plane of a preselected great circle course, and (3) measure the rotation of the vertical in this plane to indicate progress along the course. By coupling the pendulum outputs to the aircraft control system with arrangements for automatically nulling the cross track pendulum to keep the aircraft in the plane of the desired great circle course, and comparing the processed output of the range pendulum with the programmed flight position of the aircraft to control location along the track, the SPIRE system could be made to follow a preset flight plan with indications of cross track deviations along the course, and signal mission completion when the objective was reached.

During preflight alignment, the angle between the line of nodes gimbal and the range gimbal was set and clamped so that the proper angle existed from the polar axis to the range axis. For initial adjustment purposes only, the correct range angle was set between the vertical package (unit carrying the two pendulums), and the range gimbal. The stabilization servo-drives were then energized, and the signals from the two pendulums and an externally mounted photo theodolite were resolved and used to torque the gyros thereby aligning the vertical package to the local direction of gravity and turning the range axis to the correct aximuth. With the system geometry established, SPIRE was ready to supply control commands to the autopilot for automatic operation, and indications to readout dials for monitoring by human operators.

Figure 20 is a photograph of the SPIRE system as it appeared during engineering tests in the Laboratory during the latter part of 1951. The system was much larger than could be accepted for aircraft, and weighed about 2800 pounds. Although weighing some 25 percent less than FEBE, it was still much too great for flight use. However, the objective of all-inertial operation had been attacked, and patterns of design for components and subsystems suitable for aircraft purposes were emerging that held real promise for practical guidance equipment with all the qualities needed for flight operations.

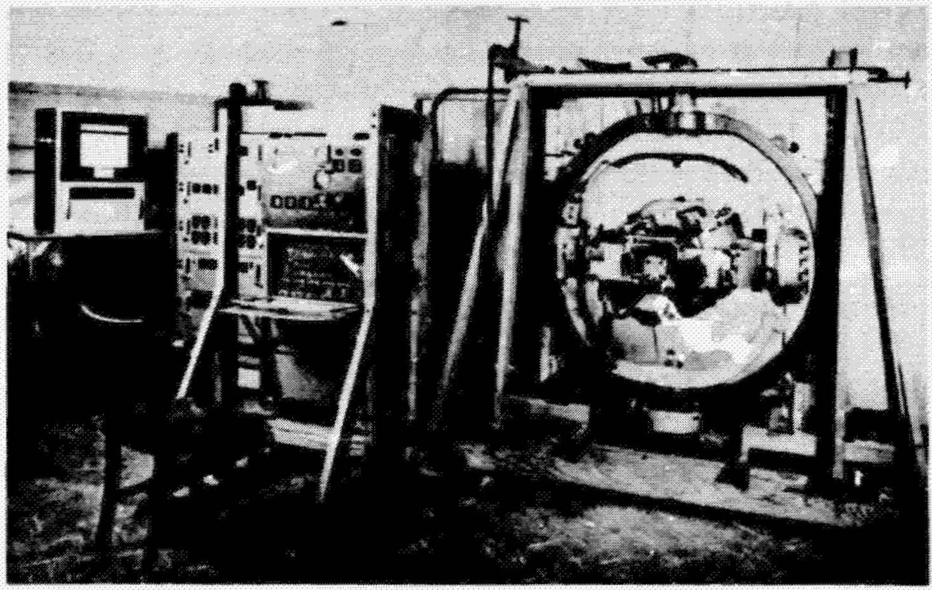

Fig. 20
Photograph of Spire System on Test in Laboratory

CONCLUSION

The "20-Year Rule" set by the Academy History Committee limited this memoir to the 1935-1951 period at the Massachusetts Institute of Technology. During this span of years the basic ideas of inertial guidance appeared, were implemented in experimental hardware, and flight tested to demonstrated engineering feasibility. It is unfortunate in a way that in 1951 the SPIRE flights had not yet started and marine, missile, space, and commercial aircraft developments were still a few years in the future. I will not mention the equipments built and results achieved during the 1950s beyond noting that the technology pioneered, would be followed by considerable production and wide-spread use, based on concepts that were no more than misty ideas in 1935.

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