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**A HISTORY OF
INERTIAL GUIDANCE**

By
F. K. Mueller

419538



ARMY BALLISTIC MISSILE AGENCY

REDSTONE ARSENAL, ALABAMA

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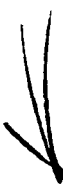
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⑦ BY
F. K. MUELLER,

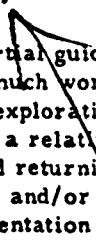
GUIDANCE AND CONTROL LABORATORY
DEVELOPMENT OPERATIONS DIVISION

416.

FOREWORD



This report deals with the development of inertial guidance systems for ballistic missiles. It covers the evolution of guidance devices from the early days of experimentation during the 1930's, through the operational use of the workhorse LEV-3 system on the German V-2 rockets, to the reliable and accurate guidance mechanisms of today. Personnel of the ABMA Laboratories, with experience dating as far back as pre-World War II days, made great contributions to the advancement of the art, science and engineering of inertial guidance systems.



Although inertial guidance systems have been greatly improved in the past few years, much work remains to be done if adequate guidance is to be provided for the exploration of outer space. Present systems can provide guidance only for a relatively short distance. Vehicles travelling to or landing on planets and returning to the earth will require even more precise guidance systems and/or supervision by celestial tracking. New concepts in guidance instrumentation may have to be developed.

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Chapter 1

HISTORICAL BACKGROUND

Inertial guidance is a self-contained system which can guide and control missiles without signals from the ground. The guidance to the target includes sensing and correction of disturbing forces such as side winds and uneven thrust from power plants. The gyroscopic principles on which inertial guidance is based are taken from Newton's laws of motion.

Inertial guidance has been adapted for use in ballistic missiles so that they can now be sent to targets thousands of miles away. This type of guidance is particularly useful for long-range missiles operating over hostile territory. Because the inertial guidance system does not rely on electronic signals from the ground, it cannot be jammed by electronic countermeasures.

Measurement of accelerations is the basis for most inertial guidance systems. In the most recently developed systems, a gyro-stabilized platform serves as a basic reference for measuring the magnitude and direction of the accelerations. This platform is stabilized by three gyroscopes, one for each of the three missile axes (Figure 1). Gyro-type accelerometers, mounted on the stabilized platform, measure accelerations in predetermined directions.

Inertial guidance systems for missiles were not developed overnight. In 1934 the Germans first attempted to control a missile by inertial means. This first system was rather crude, but it paved the way for present day inertial guidance systems. During the past 25 years, instruments and controls have been developed and refined toward achievement of pin-point accuracy in guiding missiles over long distances. The successes to date are but the beginning. Still greater refinements are necessary to guide missiles accurately over longer distances and into outer space.

EARLY ROCKETS

A-2 Rocket (Figure 2)

The German-developed A-2 rocket was one of the first rockets using a simple gyro system for guidance. A large gyro was placed into the center of the rocket between the oxygen and fuel containers. The axis of the gyro was

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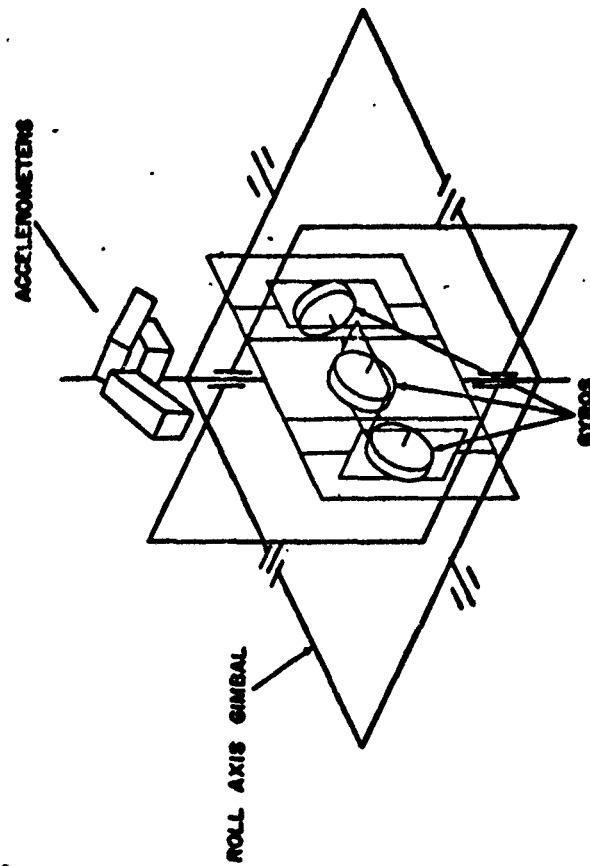
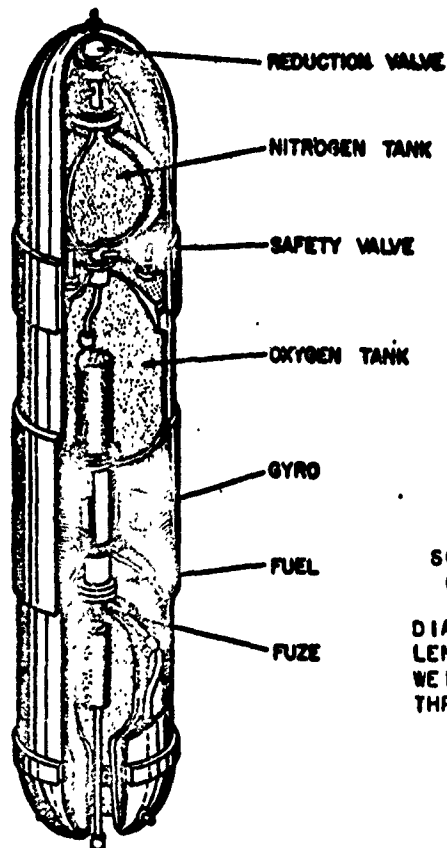


Figure 1. Platform Stabilized for Three Planes of Motion

Historical Background



SOME IMPORTANT DATA OF THE A-2 ROCKET

DIAMETER	12"
LENGTH	5-1/2'
WEIGHT	400 LB.
THRUST	650 LB.

Figure 2. German A-2 Rocket

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rigidly mounted to the rocket. The gyro wheel coasted freely during the flight. It was supposed to keep the rocket in the correct attitude by brute force. Two A-2 rockets were launched in 1934 from guide towers on the Borkum Island in the North Sea. Both rockets soared to 7000 feet. However, it was apparent that such a system had severe shortcomings, as it required a large and heavy gyro, rigidly mounted and thus presenting intercoupling problems between the gyro and the rocket.

The Goddard Rocket

Almost simultaneously with the A-2 development, the American rocket pioneer, R. H. Goddard, worked in this country on his first gyroscopically-controlled rocket. He fired it in the spring of 1935. It should be noted that this was the first time that the attitude of a rocket was sensed by a gyro, and the attitude indications were used to operate jet-vanes in order to control the rocket. Furthermore, a tilt program was incorporated to turn the rocket from vertical take-off into horizontal flight. The altitude reached was 4,800 feet and the distance covered was 2.5 miles.

A-3 Rocket

The A-3 series of rockets launched in 1937 were the first missiles to incorporate trajectory control. The complicated guidance system was designed to launch the rocket vertically. The attitude of the rocket was controlled by three rate gyros. Accelerations and velocities were measured in pitch and yaw by spring mass accelerometers and oil damped integrators mounted on a two-axis gyro-stabilized platform (Figure 3). The principle of this system was sound but it was too complex to be practical with the instruments which could be built at that time. Five A-3 rockets were launched in 1937, but their control system was not adequate to handle the rockets under flight conditions.

A-5 Rocket (Figure 4)

The A-5 type of rockets, an improved version of the A-3, used a simpler guidance system. This was a 3-gyro, 3-axis stabilized platform that provided attitude control and a tilt program. Angular deviations were sensed by rate gyros located above the stabilized platform, and the signals were mixed and fed into a control system also mounted above the platform.

Historical Background

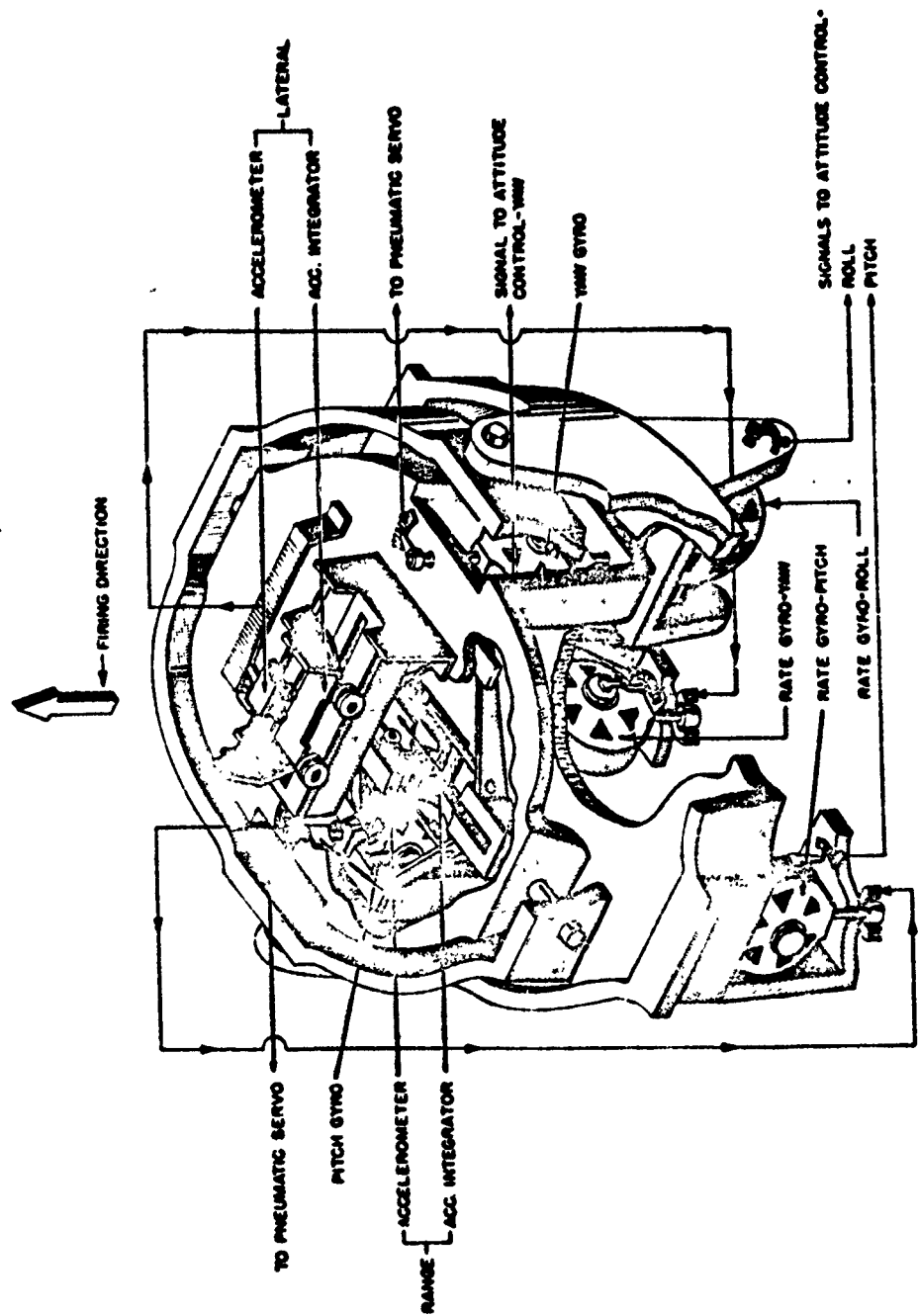
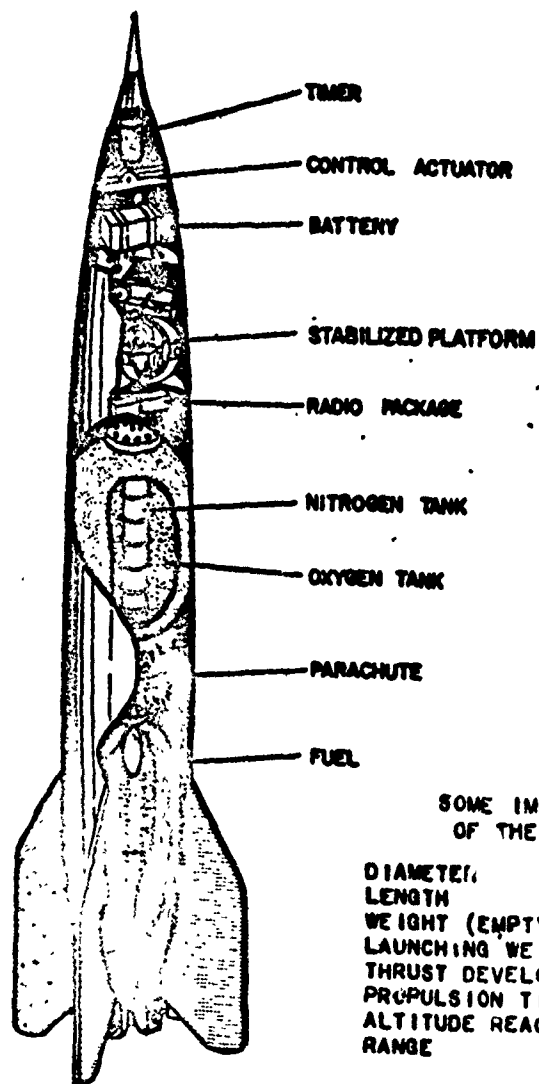


Figure 3. Stable Platform for A-3 Rocket

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SOME IMPORTANT DATA OF THE A-5 ROCKET

DIAMETER	28'
LENGTH	22'
WEIGHT (EMPTY)	1,200 LB.
LAUNCHING WEIGHT	1,800 LB.
THRUST DEVELOPED	3,300 LB.
PROPULSION TIME	45 SEC.
ALTITUDE REACHED	13,000 METERS
RANGE	18,000 METERS

Figure 4. German A-5 Rocket

Historical Background

The complete guidance and control system was in one package, as shown in Figure 5. Connections to the jet steering vanes were made by aluminum rods. The first A-5 missile was launched late in 1939. Its guidance system was the forerunner of the one used in the V-2 rocket.

A-4 (V-2) Rocket

Two different guidance systems were developed for the A-4 missile, later renamed the V-2 (Figure 6 and 7). The first was the familiar LEV-3 guidance system (Figure 8). The LEV-3 consisted of two free gyros, control potentiometers, pendulums, servo motors and other components necessary for mounting and adjustment. One of the free gyros controlled yaw and roll deviations while the other controlled pitch deviation and tilt program. A gyro-type accelerometer was developed which incorporated a preset device for propulsion cut-off (Figure 9). This system was straightforward and very dependable. A great many of these missiles were fired with an accuracy of 5 km (3.1 miles) circular probable error (CPE) over a range of 200 km (125 miles). The use of an electronic guide beam for additional yaw control reduced the lateral error to about 800 meters (1/2 mile).

The second system developed for the V-2 was similar to modern guidance systems, but with components not nearly as accurate as those used today. A 3-gyro, 3-axis stabilized platform (Figure 10), 20 inches in diameter and weighing 100 pounds, was suspended by external gimbals and provided attitude signals and a timed tilt program. Both an ac and a dc power supply were required for operation of the platform. Servo motors and accelerometers were operated by one- and two-stage on-and-off contacts. Use of gyro rotors with a large angular momentum made the system simple, stable and reliable.

Cut-off of propulsion was controlled by an integrating gyro-type accelerometer coupled to a disk integrator. These were mounted on the stabilized platform along the major axis of the missile (Figure 11). This device calculated velocity and distance and determined propulsion cut-off time.

Yaw was controlled by an accelerometer consisting of a coil moving in a magnetic field. The integrations were performed in capacitor networks. Test firings demonstrated a 50 percent probability that range error would not exceed 4.2 km (2-1/2 miles) and lateral error would not exceed 2.4 km (1-1/2 miles) for a range of 200 km (125 miles).

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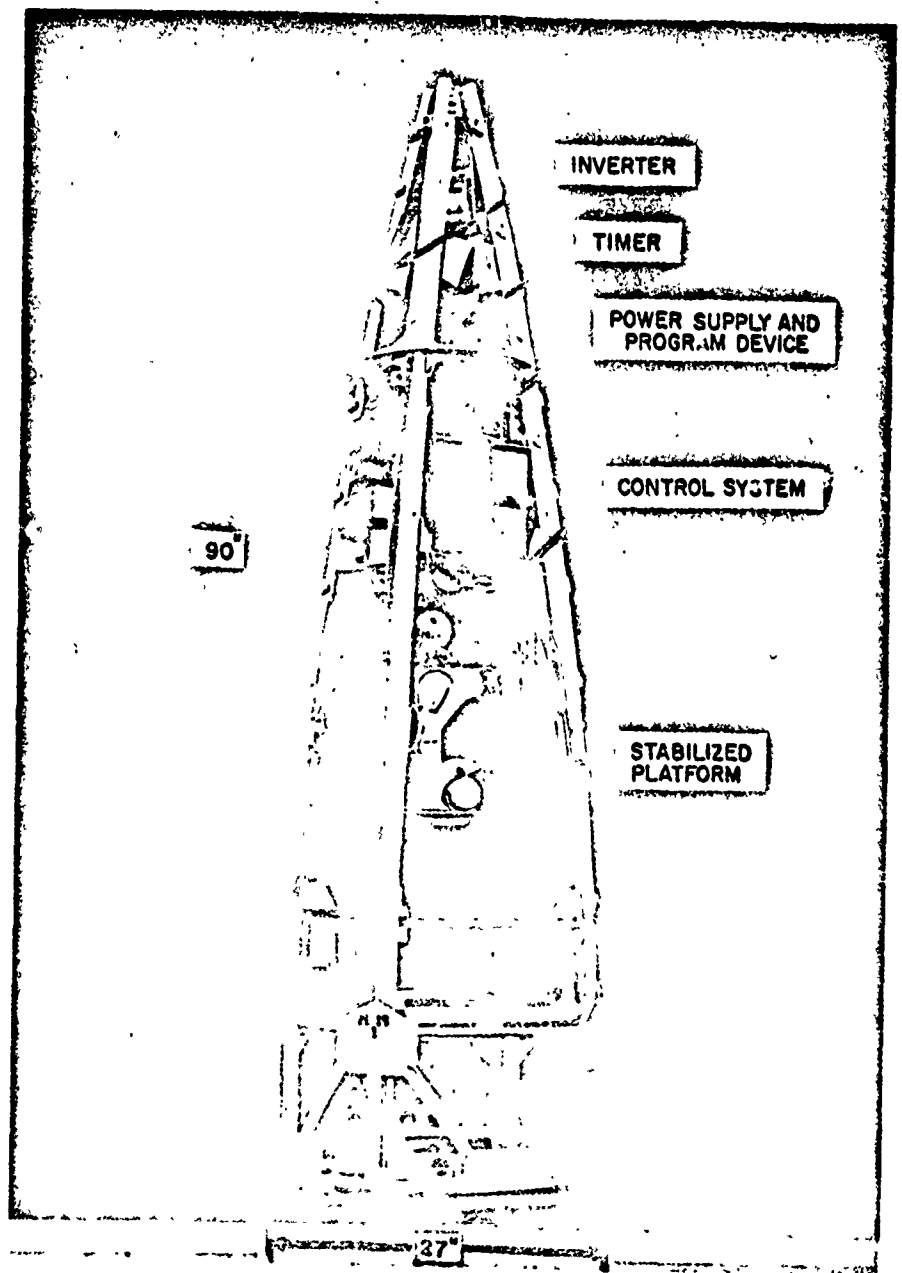


Figure 5. Guidance and Control System for A-5 Rocket

Historical Background

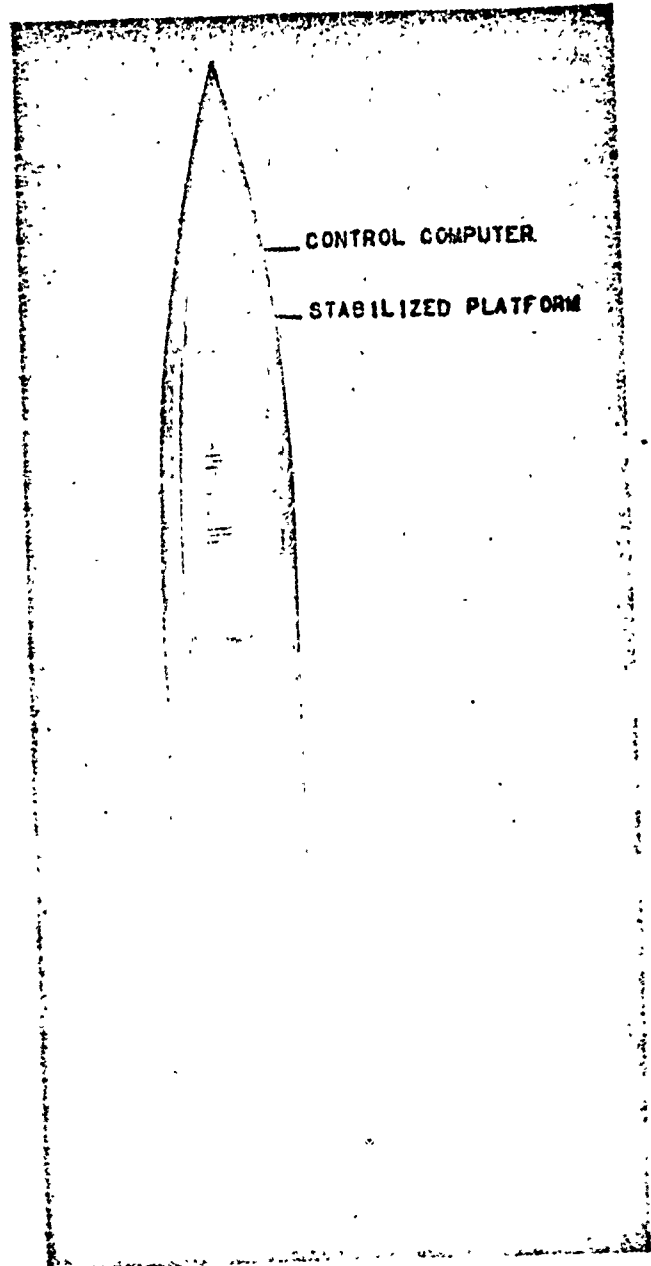


Figure 6. German A-4. Rocket

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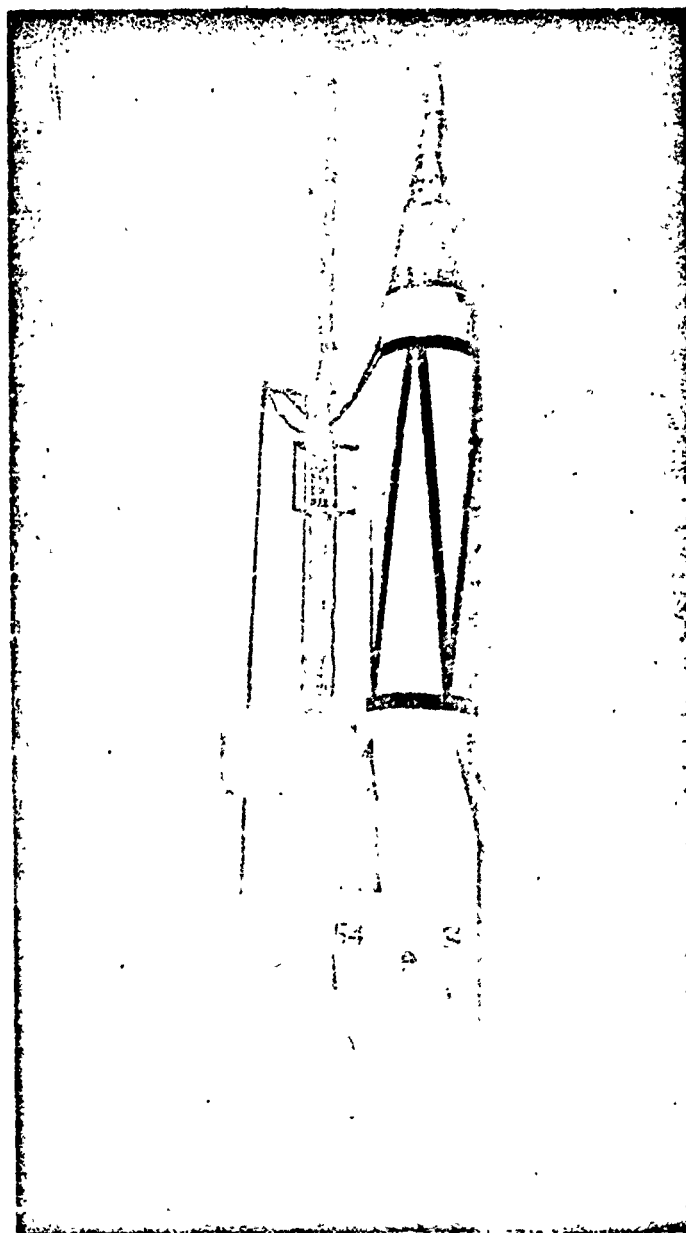


Figure 7. German V-2 Rocket

Historical Background

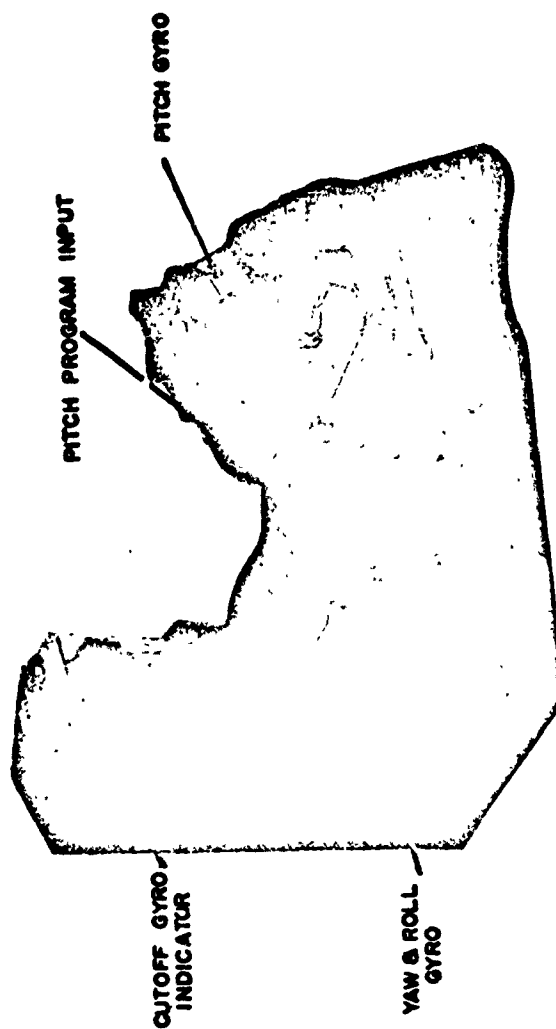


Figure 8. LEV-3 Gyro System

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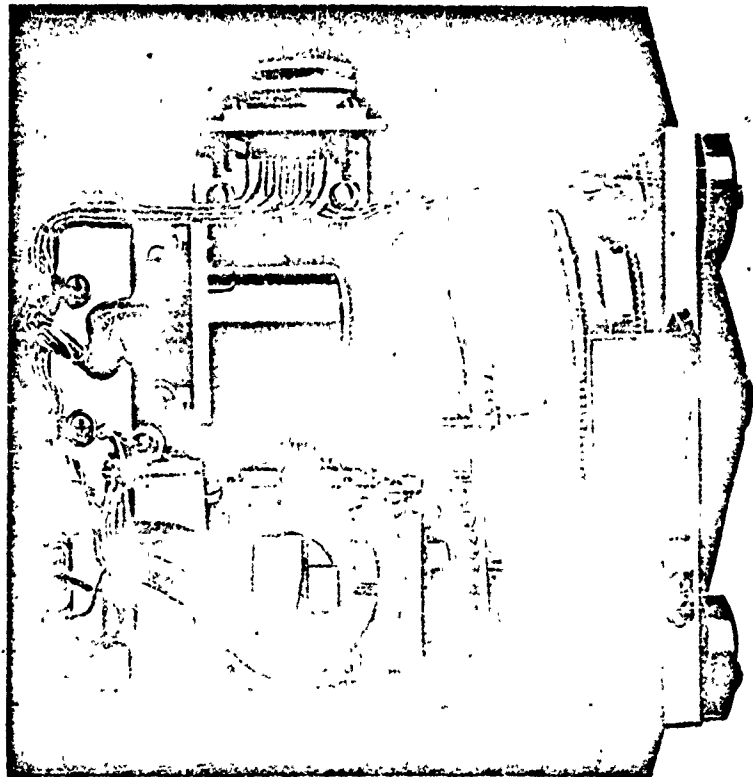


Figure 9. V-2 Propulsion Cut-off Device, System I

Historical Background

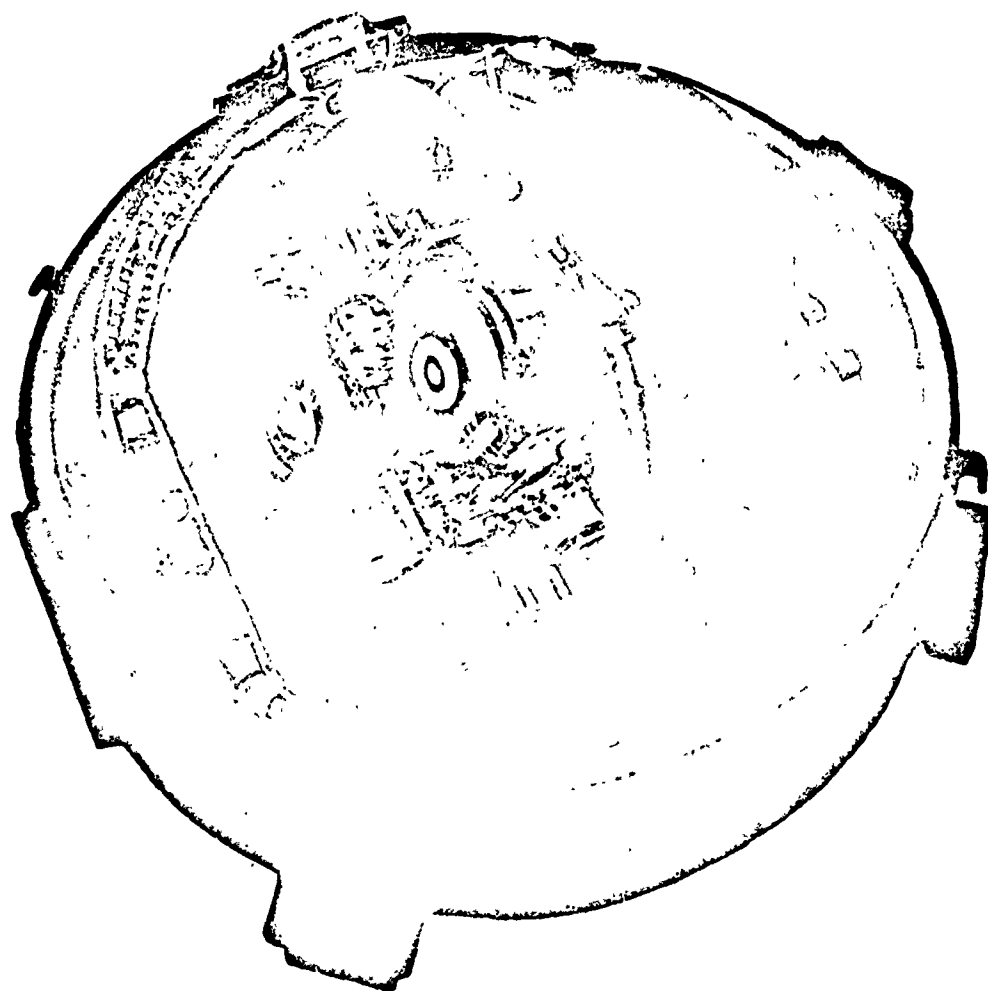


Figure 10. A-4 (V-2) Stabilized Platform

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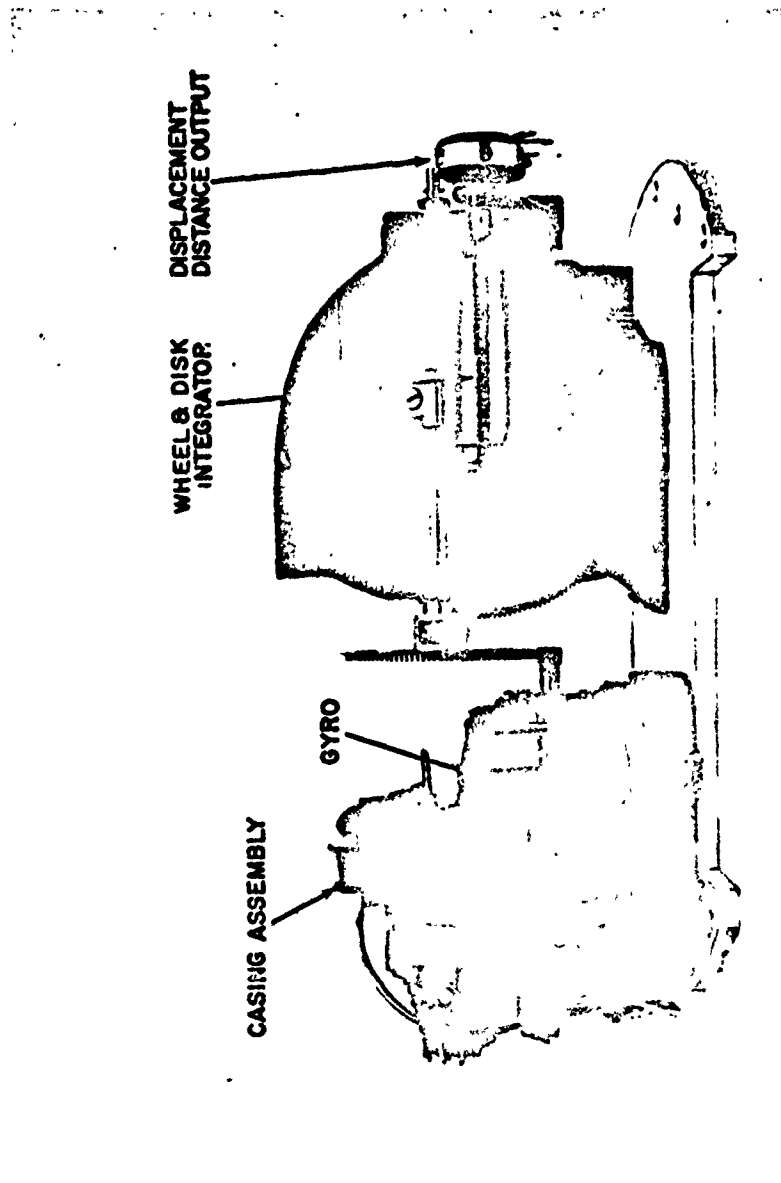


Figure 11. V-2 Propulsion Cut-off Device, System II

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The drift rate of early gyroscopes used on aircraft to indicate attitude and heading was about 10° /hour. The drift rate of gyroscopes used on present missiles is only a fraction of this value, but further reduction of gyroscope drift will be necessary to provide the accurate stabilization required for future platforms.

Also, in order to achieve high impact accuracy in range direction it is necessary to determine thrust cut-off relative to velocity and the distance covered. This problem was eventually solved by use of instruments which compute the first and second integral of acceleration.

EARLY GYROS AND ACCELEROMETERS

Spring-Mass Accelerometers

A spring-mass accelerometer of the type used in the A-3 missile is shown in Figure 12. At zero acceleration, the mass is centered by the supporting springs. If the housing is accelerated along its sensitive axis, the weight tends to resist the acceleration and is displaced from the center to a distance directly proportional to the acceleration. This displacement is sensed by a pick-off potentiometer which originates a signal proportional to the displacement (and therefore to the acceleration). This type of accelerometer is neither sensitive nor accurate enough for modern missiles which encounter a wide range of accelerations.

Integrating Accelerometers

One of the problems encountered with the V-2 missile was accurate measurement of velocity and position during flight.

A method of guidance was needed, independent of ground-based reference signals. To achieve proper flight control, the acceleration measurements, which are the basic information in inertial guidance, must be integrated.

Several integrating accelerometers were developed for missile guidance, using mechanical, electrical and electrochemical principles. These were light in weight and free from jamming.

MECHANICAL INTEGRATING ACCELEROMETER - The first unit to be flight tested was the Mueller mechanical integrating accelerometer, a gyroscopic device shown in Figure 13. This is primarily a range device to cut off propulsion when the rocket attained the velocity required to reach its target. The

PROBLEMS IN THE DEVELOPMENT OF GUIDANCE SYSTEMS

Although the V-2 guidance system could hardly be said to provide pin-point accuracy, it did demonstrate the feasibility of inertial guidance. New work in theory, design and manufacturing techniques was required to:

1. Reduce size and weight of components
2. Eliminate friction in components to improve accuracy and reduce reaction time
3. Eliminate shift of center of gravity due to acceleration
4. Improve reliability and reproducibility of instruments
5. Improve computer and servo techniques

Gyroscopes are mounted in a gimbal suspension to enable them to maintain a fixed orientation in space. The most familiar example is the gyro which keeps a shipboard compass level regardless of how the ship tilts. Such a gyro uses an external gimbal system: the gyro is suspended inside a pair of rings, one of which can move within the other. In the V-2, the weight of the guidance system was reduced by use of hollow box steel gimbals instead of the conventional solid aluminum alloy rings. This structure also had better resistance to stress, but external gimbal systems are inherently bulky and components are not easily accessible for calibration, maintenance and replacement.

Among the problems which had to be overcome were the following: large accelerations tend to distort the various components as well as the entire suspension of the stabilized platform, especially the external gimbal suspension. These distortions may cause friction between components or a shift in the center of gravity, and these in turn cause undesirable precession of the stabilized platform.

Early guidance systems had to depend on ball bearings in the gyroscope precession axis. Although in industrial applications the coefficient of friction of ball bearings is considered very small, it is far too great for missile instruments.

Gyroscope drift is the deflection of the spin axis of the gyro from its initial alignment and is caused by bearing friction, shift in the center of gravity or any other torque about the precession axis. Deflection of the spin axis of a gyro causes the platform to move from its stabilized position, and this in turn causes the accelerometers to measure accelerations in false directions, resulting in guidance errors.

Historical Background

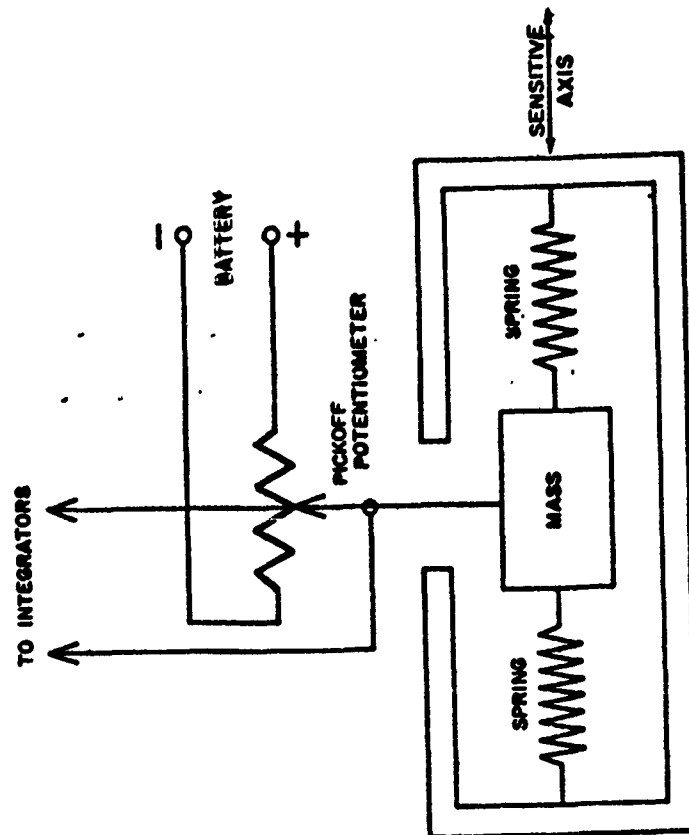


Figure 12. Spring-Mass Accelerometer

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gyroscope is supported in an unbalanced position and therefore precesses at a rate determined by the acceleration. The angle through which the gyroscope precesses is a measure of the integrated acceleration, hence of the missile's velocity. This device was very simple and reliable and was used in most of the V-2 flights.

ELECTROLYTIC INTEGRATING ACCELEROMETER - An electrolytic integrating accelerometer was developed by Buchhold and Wagner. A pivoted arm with a copper slug moving between the poles of two electromagnets unbalances an electrical bridge. The signal obtained is applied to a restoring coil in a magnetic field in series with an electrolytic cell. Current flowing in the coil and cell causes a chemical change in the cell at a rate proportional to the acceleration, and, after an interval corresponding to a predetermined velocity, the cell voltage increases suddenly. This jump of voltage can be used for propulsion cut-off.

MAGNETIC INTEGRATING ACCELEROMETER - The Schlitt integrating accelerometer (used in experimental V-2 missiles for yaw control) is illustrated in Figures 14 and 15. This consists of a coil concentric with the centerpole of a loud-speaker type magnet and free to move about a pivot. Under acceleration, the lever moves upward to close the contacts, and the coil is energized. When the contacts are closed, the resulting forces cause the coil and lever to move downward, opening the contacts. The average current through the coil is in proportion to the acceleration of the missile. This instrument provides information for one direction only, but use of a bridge circuit gives accurate data for both directions. The current may be integrated once, twice, or three times in a capacitor network to measure velocity, distance, or the integral of distance as a function of time, respectively.

Historical Background

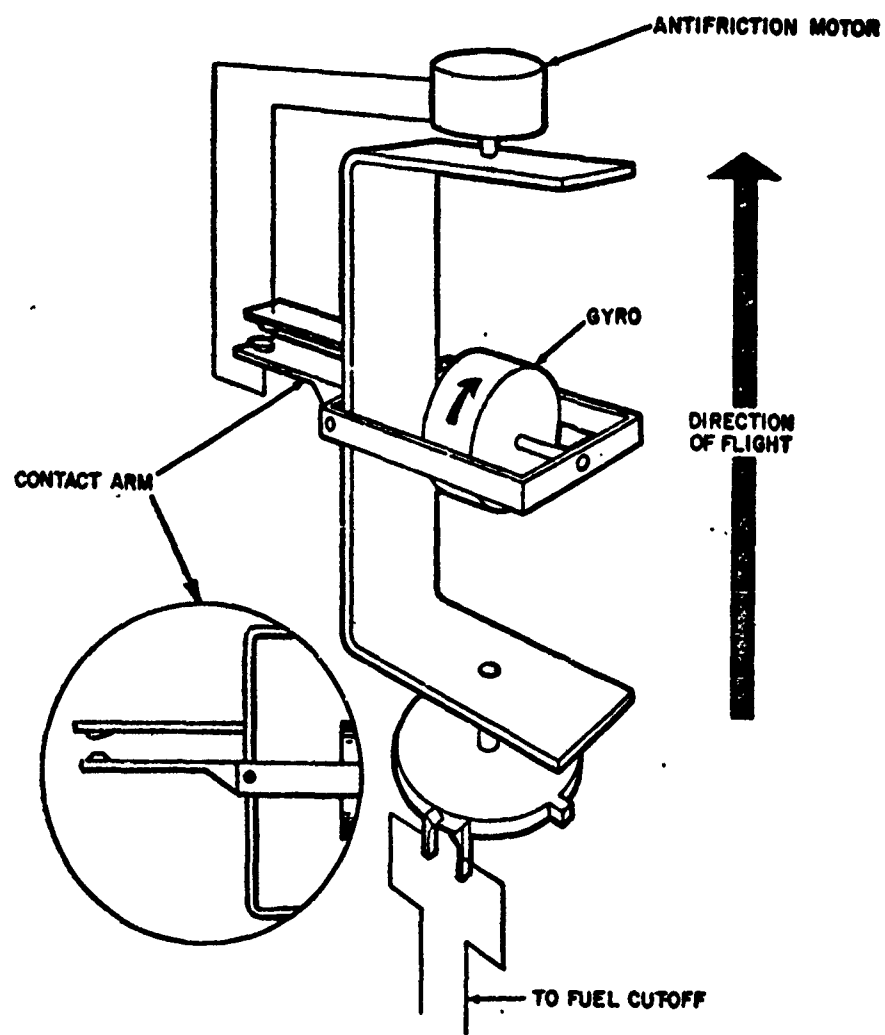


Figure 13. Mueller Mechanical Integrating Accelerometer

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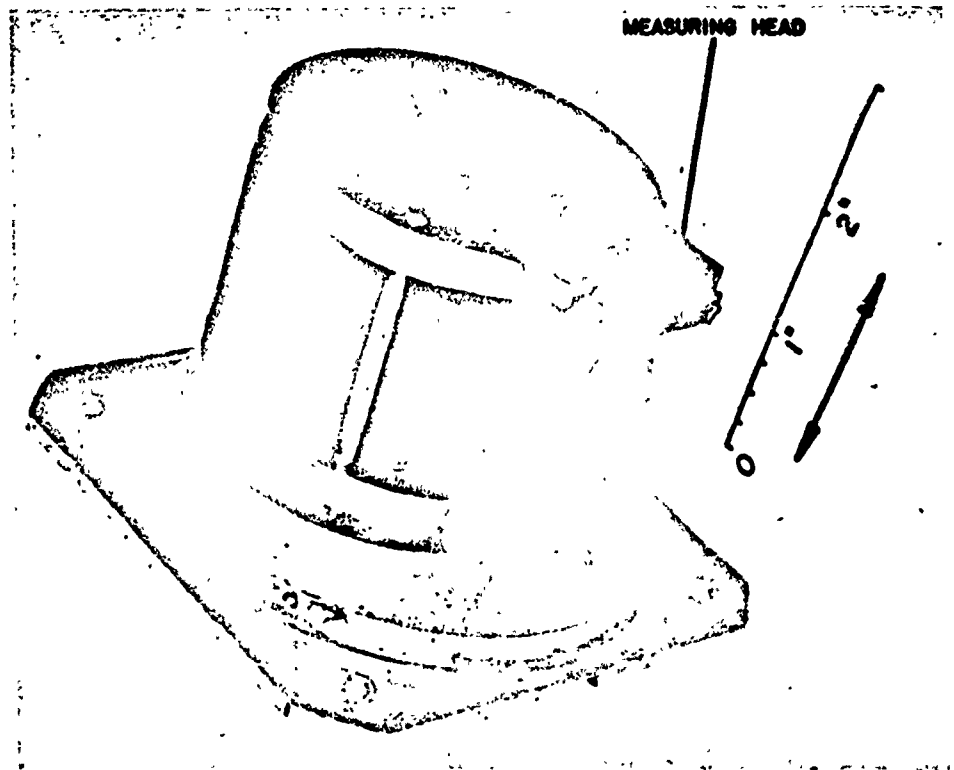


Figure 14. Schlitt Integrating Accelerometer

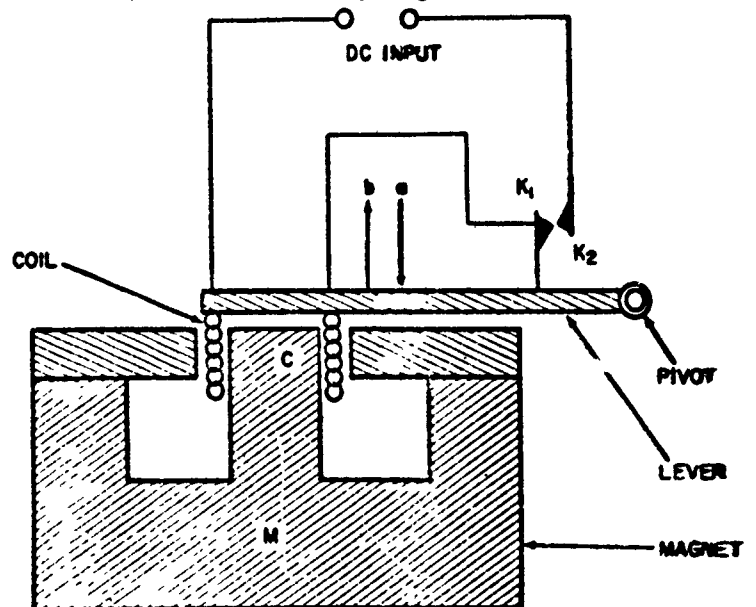


Figure 15. Schlitt Integrating Accelerometer Measuring Head

Components of Present Inertial Guidance Systems

Chapter 2

COMPONENTS OF PRESENT INERTIAL GUIDANCE SYSTEMS

A missile in flight has no route markers or guide-posts to follow in reaching its destination. Once launched, the missile is on its own and its self-contained guidance system must be able to compute speed, distance, and direction to guide the missile smoothly to its target, regardless of outside disturbances. The high speed of missiles calls for a guidance system which operates continuously and rapidly enough to detect and correct deviations before they seriously affect the trajectory.

To make the required measurements and adjustments, present inertial guidance systems use accelerometers mounted on a space-fixed platform suspended by a gimbal system. Signals from the accelerometers are evaluated by computer units which transmit the necessary commands to the actuators of the controls.

ACCELEROMETERS

Measurement of accelerations is the key to inertial guidance. The platform is stabilized and aligned to provide the mounting and reference essential for accurate functioning of the three accelerometers which measure changes in motion along the three axes. From these measurements, both velocity and distance can be computed. These accelerometers must be capable of measuring accelerations as small as a few ten thousandths of one g and as large as 10g. They must be precision-mounted on the stabilized platform with their axes perpendicular to each other. Precise machining, calibration, and good damping are required to reduce the effects of vibration and assure accuracy.

One of the most successful modern accelerometers is an air-bearing gyroscope with an unbalance weight fastened to the inner cylinder. The inner cylinder is separated from the outer cylinder by an air bearing (Figure 16). An acceleration in the direction of the precession axis causes a torque by the unbalance weight around the air-bearing axis. The torque causes the outer cylinder to precess, and the rate of precession is proportional to the acceleration.

The outer cylinder or gimbal is mounted on ball bearings. The friction in these ball bearings causes some precession of the inner cylinder and a corresponding change in the measuring direction of the accelerometer. To

A HISTORY OF INERTIAL GUIDANCE

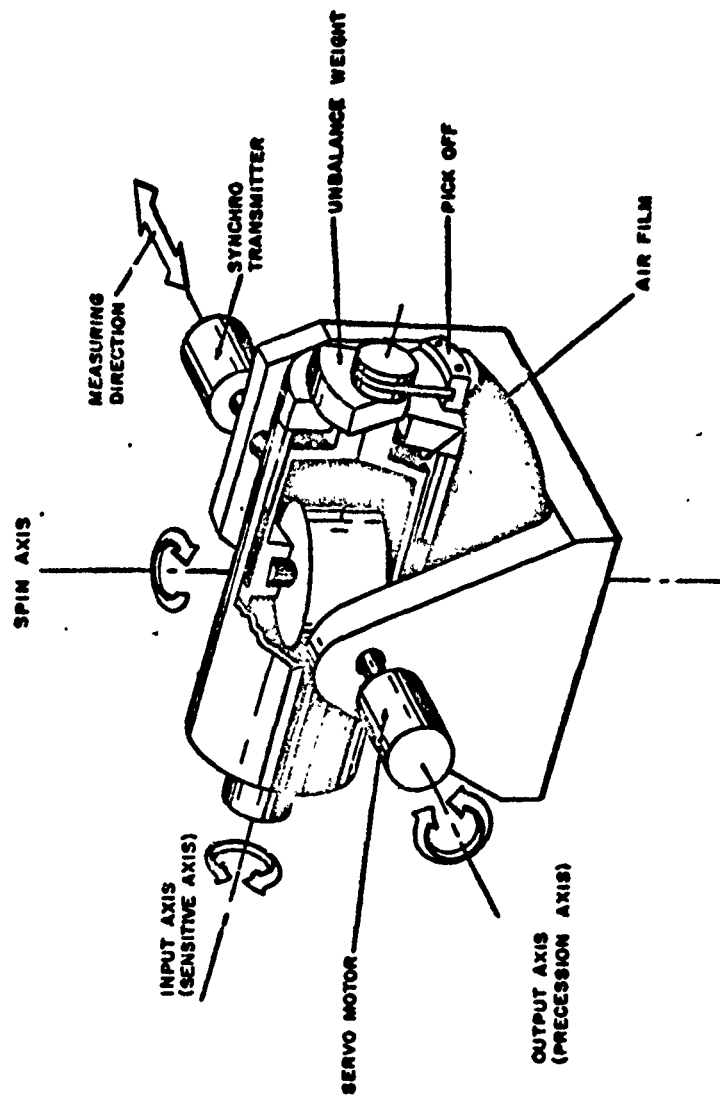


Figure 16. Air-Bearing Gyro Accelerometer.

Components of Present Inertial Guidance Systems

prevent this unwanted precession, a pickoff senses relative motion between the two cylinders and sends electrical impulses through an amplifier to a servo motor which is geared to nullify the effect of this friction torque.

In measurement of accelerations, the angular velocity of the precession shaft is proportional to the acceleration. The angular position of the precession axis indicates velocity in the measuring direction. This information, in the form of voltages produced by the synchro-transmitter, is transmitted to the computer for evaluation. The computer in turn sends any necessary commands to the control actuator system.

STABILIZED PLATFORM

The stabilized platform is the reference base for the inertial guidance system. Its position in space is fixed by three gyroscopes with their reference axes perpendicular to each other. Whether on the earth or in outer space, the platform maintains the same orientation.

In early missiles, the platform was suspended by three concentric, interlocking gimbal rings (Figure 17). Use of this conventional external-gimbal system in missiles disclosed several serious faults: it proved to be too bulky and heavy, and under the tremendous acceleration of missile firing it was deformed to an extent that accuracy was impaired. Development of a suspension by internal gimbals has made the stabilized platform an accurate and dependable reference base. Figure 18 shows a stabilized platform with its internal gimbals, air-bearing gyroscopes, accelerometers, and pendulums.

Internal Gimbal Suspension

The internal gimbal system is, essentially, the conventional gimbal system turned inside out. Figure 19 shows the bearings in the center of the device. The gyros, accelerometers, and pendulums are fastened to the outside ring or stabilized platform. The outer ring can rotate freely on ball bearings through 360 degrees, but the inner gimbal can move in yaw and roll only through a limited arc (until it touches the outer gimbal ring). The 360-degree rotation allows the missile to be tilted from the vertical about the pitch axis. The limited movement of the gimbals in roll and yaw is sufficient because the missile moves about these two axes through only a small angle before the controls correct the error. Pickoffs and servos are mounted on the gimbals for each of the three axes to measure and correct deviations.

A HISTORY OF INERTIAL GUIDANCE

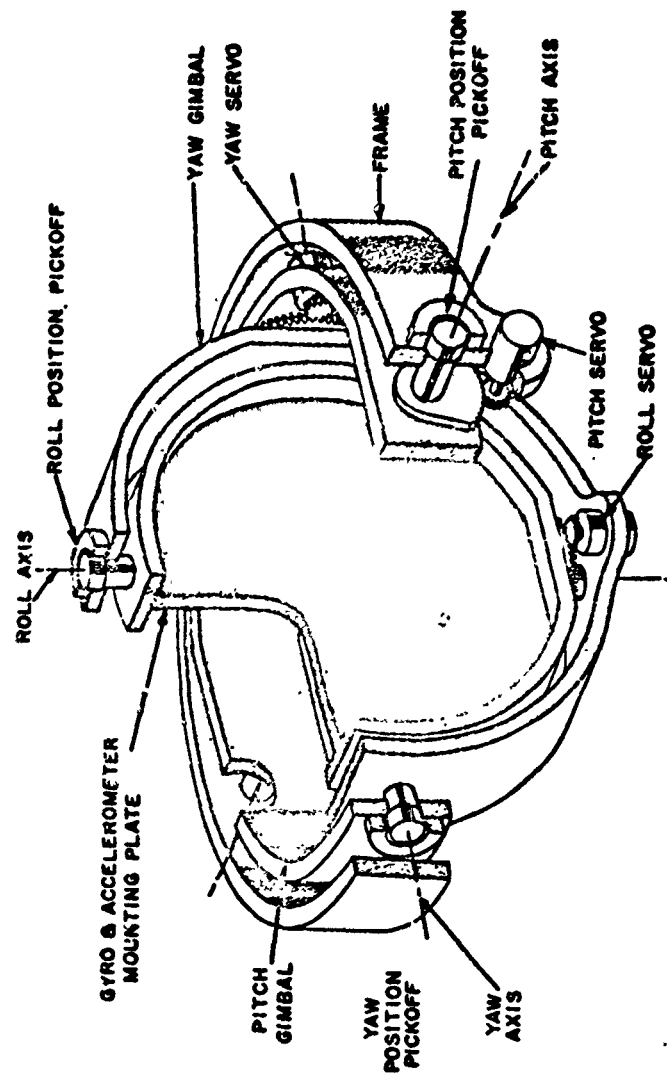


Figure 17. External Gimbal System

Components of Present Inertial Guidance Systems

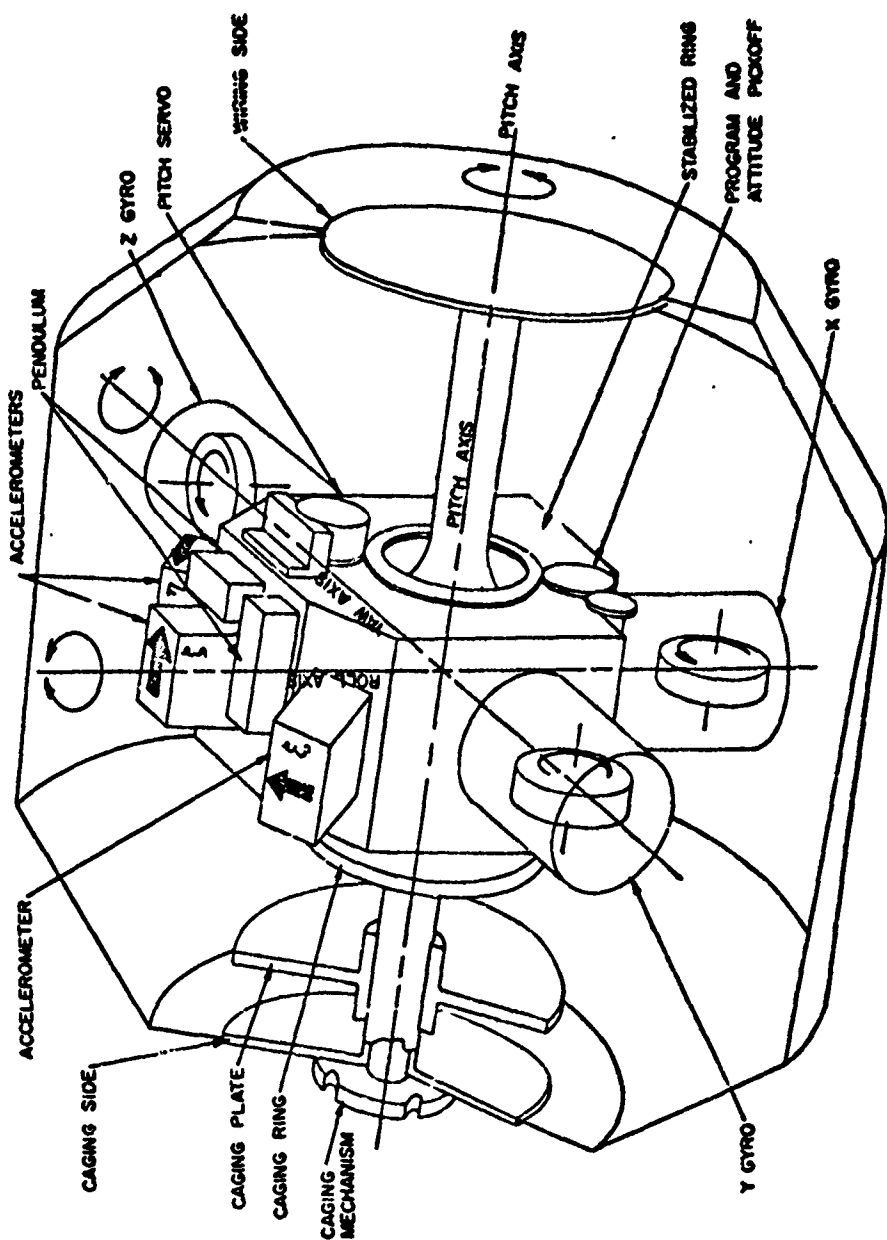


Figure 18. Stabilized Platform

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The internal gimbal system has several advantages over the external gimbal system. It saves weight and space and permits the use of more rugged

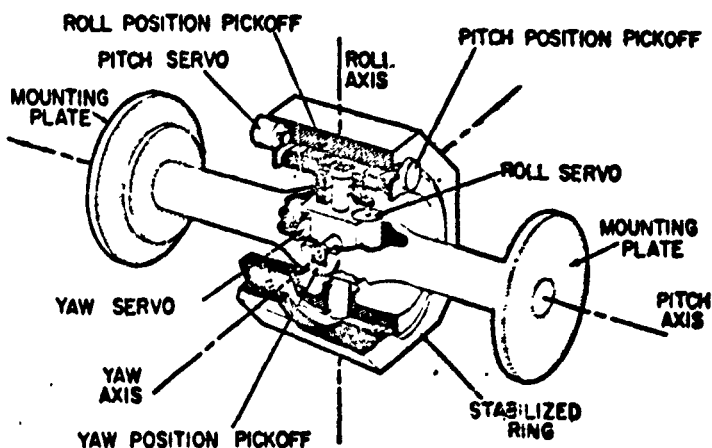


Figure 19. Internal Gimbal System

parts. The short, sturdy axles undergo much smaller elastic deformations during missile acceleration and have considerably smaller moments of inertia than gimbal rings in the external gimbal system. Also, instruments mounted on the outer ring are readily accessible for calibration or replacement.

Gyroscopes

Three gyros are attached to the outer mounting ring of the internal gimbal system to stabilize the platform: one for each of the three reference axes -- pitch, yaw, and roll. Each gyro spin axis is perpendicular to the axis which it stabilizes. For example, the pitch gyro is mounted so that its spin axis is parallel to the roll axis and perpendicular to the pitch axis of the missile.

The three gyros are similar. The rotor is mounted on ball bearings within a cylinder which is supported by an air bearing (Figure 20). This air bearing is practically frictionless, making the gyro far more sensitive than those employing ordinary bearings and reduces the unwanted precession caused by friction in other types of bearings.

A disturbing torque occurring about the axis controlled by a gyro, causes rotation about the precession or air-bearing axis in proportion to the disturbing

Components of Present Inertial Guidance Systems

torque. Since the rotor is mounted inside the inner cylinder of the gyro, the cylinder undergoes the same precession as the spin axis. This motion is

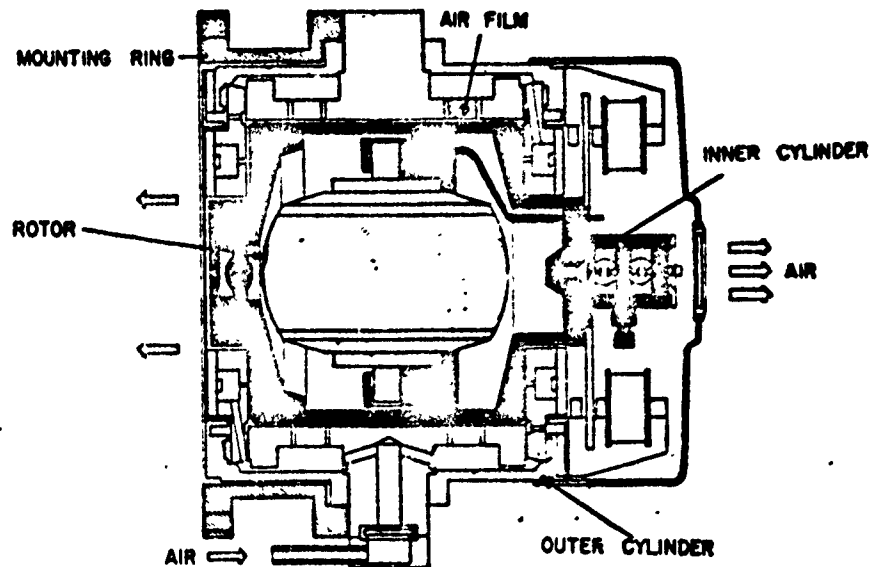


Figure 20. Cross Section Through an Air-Bearing Gyroscope

sensed by a pickoff which sends a signal to the servo amplifier. The amplified signal actuates a servo motor which produces the corrective force required to cancel the effect of the disturbing force and return the gyro's spin axis to its original position. The combined effects of the three gyros in maintaining stability about their assigned axes keep the stabilized platform in its space-fixed position so that it can be used as a basic reference to control the missile's flight. By introduction of a programmed flight schedule, the same devices can be used to keep the missile essentially tangent to a precalculated trajectory.

Low-Friction Bearings

Before the development of low-friction bearings, missile flights were subject to inaccuracies caused by drift of gyroscopes and gyro-type accelerometers and by inaccurate alignment of the stabilized platforms prior to launching. These inaccuracies were mainly caused by the friction of the conventional bearings then used.

A HISTORY OF INERTIAL GUIDANCE

Two different types of bearings have been developed to reduce the friction, both employing a fluid medium to support the shaft. The first type uses a high density liquid to float the precession axis; the second, compressed gas or air.

The liquid type consists of an outer case which seals in the high density liquid and the floating part. The density of the liquid is the same as the mean density of the floating part. Since the part floats freely in the liquid, a pinion bearing is required for axial alignment. While this liquid-type low friction bearing is a great improvement over conventional ball bearings, considerable viscous damping occurs when it is used.

In air bearings (Figure 21), the floating part is supported in a manner similar to a ping-pong ball held suspended by a stream of air. The floating part is separated from the housing by a film of air about 0.0015 inch thick. In one type of air bearing, compressed air enters the space between the part and the housing through the air inlet, air chambers, and distribution holes, and leaves through the air outlets. The holes, a few thousandths of an inch in diameter, distribute the air evenly around the bearing to maintain alignment.

Another kind of bearing is presently under development. It is designed as a high speed bearing which would support the spinning wheel of the gyro motor itself. Such a bearing would have considerable friction, but no wear.

Pendulums

The accuracy of an inertial system in guiding a missile to target depends in a large measure on the accuracy of pre-launch alignment of the stabilized platform. Precise alignment of the platform involves several factors. The launching site and the target are points on the rotating earth. But in flight, the inertial guidance system has to be space-fixed. This means that the gyros must initially be set to hold the platform in an appropriate position in relation to the rotating earth; then, at the moment of launch, they must change their function to hold the platform in a space-fixed reference system.

The coordinates of the stabilized platform must also be aligned with the missile's axes. Furthermore, a missile standing upright on a launching pad aways in the wind and experiences small tremors or oscillations which add to the difficulties of alignment.

For the above reasons, the inertial system is aligned independently of the missile structure, and the two are coordinated at the moment of launch. To handle this task a special type of plumb-line detector has been developed, the air-bearing pendulum, which meets the requirements for extreme sensitivity and also has high zero-point stability. Two air-bearing pendulums are mounted

Components of Present Inertial Guidance Systems

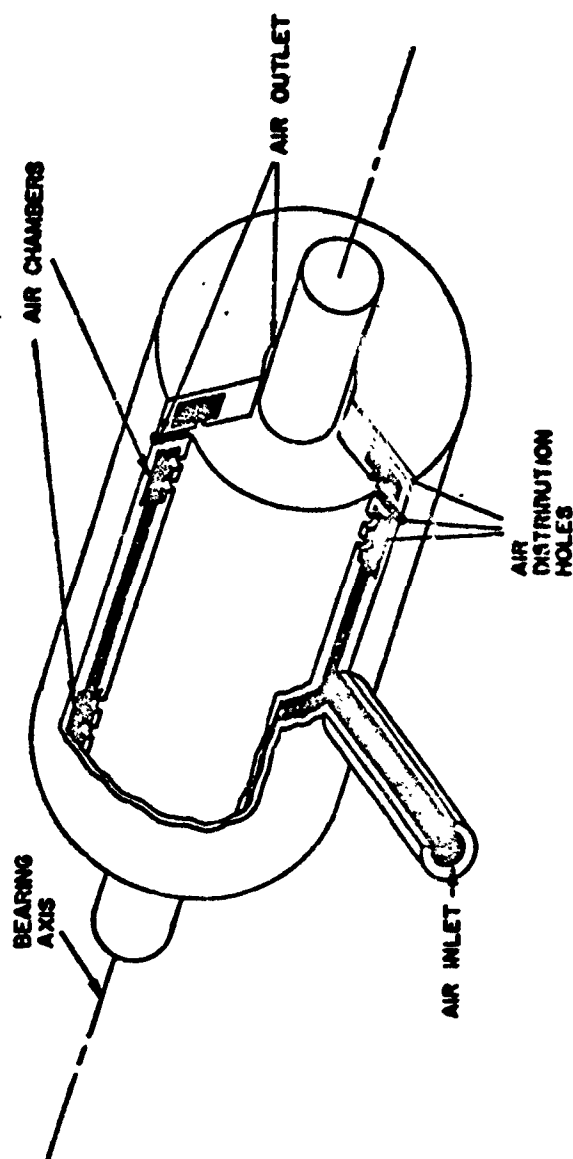


Figure 21. Distribution Hole Type Air Bearing

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on the outer gimbal or stabilized platform of the internal gimbal system. These pendulums sense the local horizontal and establish a reference for initial platform setting and calibration. Servo loops, air bearings, and damping chambers make these pendulums sensitive, quick acting and less susceptible to vibration disturbances than pendulums with other types of bearings.

Each pendulum consists of damping chambers, an air bearing, and a slug floating in a balanced electromagnetic field provided by a transformer (Figure 22). When the iron core is centered in the transformer, equal voltages are

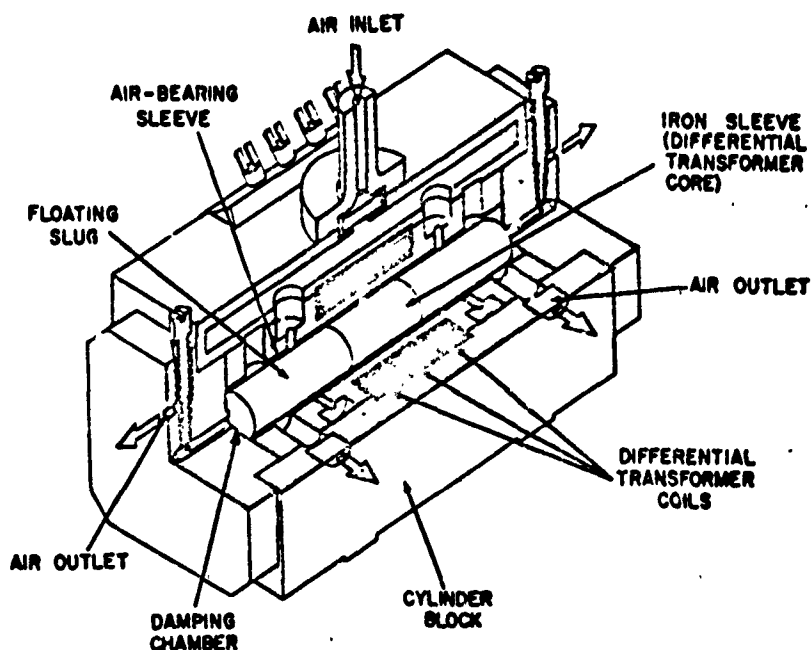


Figure 22. Air-Bearing Pendulum

induced in the two secondary coils at the ends. Movement of the float due to gravity causes an imbalance in the magnetic flux so that unequal voltages are induced. This produces an output voltage proportional to the core movement which is used to initiate a servo loop and return the platform to its proper position.

A precalculated bias voltage, corresponding to the component of the earth's rotation in the direction of the aligned axis, is added so the pendulum can sense about a null point instead of being constantly in error due to the change in direction of the local vertical as the earth rotates. This has the effect of slaving the stabilized platform to an earth-fixed coordinate system until the moment of launch.

Components of Present Inertial Guidance Systems

At launching, the air-bearing pendulums and earth-rotation biases are disconnected and the platform becomes space-fixed. As the gyros take over their task of resisting angular motion, the pendulums used for alignment of the stabilized platform have no further function.

COMPUTERS

The function of the computers is to combine the various data from the sensors and compute the appropriate signals to command the flight controls. Sensing instruments on the stabilized platform send deviation data to the computers. The computers evaluate the information from any one sensor to take into account precalculated data, and data from the other instruments. Then, through servo mechanisms, the computers cause the actuators to move the appropriate flight controls to make the required correction.

Computer units are made up mainly of three components: mixer, integrator, and differentiator. Figure 23 shows the relationship of the computers to the other components of an inertial guidance system.

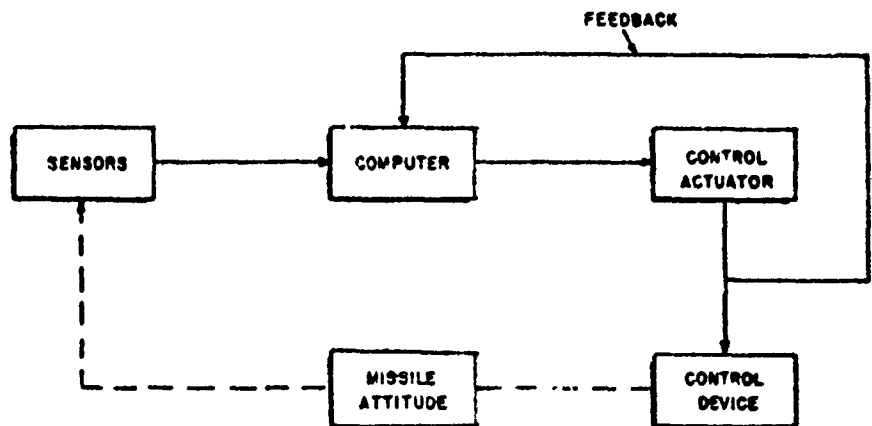


Figure 23. Schematic Diagram of an Inertial Control System

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Mixers

Mixers combine information from several sensors. For example, course is influenced by crosswinds, missile attitude, and lateral missile speed. The individual sensors detecting these three variables transmit error signals which are mixed together so that each of the variables has a proportional influence on the total corrective movement of the flight control. This mixing is usually a matter of addition or subtraction of sensor signals to signals from the control actuator feedback.

Integrators

An integrator computes the cumulative values of variable measurements such as deviation from the planned trajectory, and its output usually goes to a mixer.

Several types of integrators have been devised. Electrical integrators include the thermal integrator, the resistor-capacitor integrator, the resistor-induction combination, the amplifier-resistor-capacitor network, and the variable-speed motor. Mechanical integrators include the integrating gyroscope and the ball and disk integrator, which are used in most operational guidance systems.

In the ball and disk integrator, a disk is rotated at a constant velocity by a synchronous motor (Figure 24). The distance of the ball from the center of the disk corresponds to the input value. The greater the input value, e.g., velocity, the further away from the center the ball moves, and the faster the ball rotates. A roller in contact with the ball measures the speed of rotation and provides the integrated value. Electrical connections to potentiometers pick off voltages corresponding to input and output values, e.g., velocity and distance.

Differentiators

The differentiator reduces the time lag for control operations and therefore improves the stability of the missile in flight. As a sensor transmits information on attitude, velocity, or position, the rate component produces a signal proportional to the rate of change of the input. The rate output signal is mixed with the original deviation signal so that the command to the flight control is correct both for amount and time.

Differentiators may be electronic or mechanical. Resistor-capacitor, resistor-inductance, or resistor-capacitor-amplifier combinations similar to those used as integrators can be wired to produce differentiation instead of

Components of Present Inertial Guidance Systems

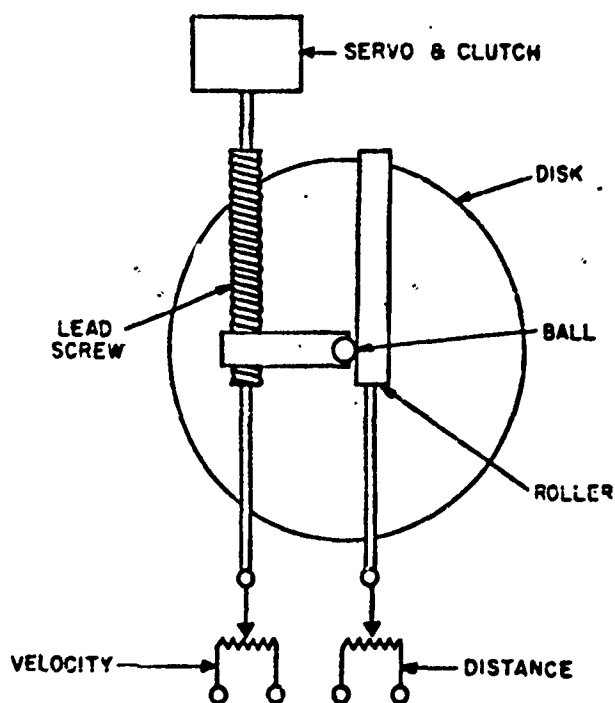


Figure 24. Ball and Disk Integrator

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integration. The mechanical ball and disk integrator can also be arranged to produce an output proportional to the rate of change.

*RATE
GYRO*

A special type of gyroscope, the rate gyro, has been designed to produce a rate signal, and this is used in some operational inertial guidance systems. The gyro, restrained by a spring that tends to return the axis to the zero position, precesses a few degrees in one plane as a result of a force on the gimbals caused by movement of the missile. This precession is proportional to the rate of deviation and is transmitted by a pickoff as a rate signal.

ACTUATING DEVICES

Flight controls are connected by mechanical linkages or cables to actuators such as electrical motors or hydraulic cylinders. The electro-hydraulic actuator system described below is used on most long-range missiles today.

The actuator assembly is mounted in the rear part of the booster unit and consists of two hydraulic cylinders and pistons (Figure 25). One end of each combination is attached to the missile shell and the other to the thrust chamber which is mounted so it can swivel up and down and from side to side. A pump supplies oil under pressure through a relief valve, an accumulator, and a transfer valve to the control actuators, and back to the oil reservoir. Signals from the computer unit to the solenoid-operated transfer valve direct the flow of oil so that the pistons move in the proper direction. The magnitude of actuator movement is proportional to the volume of oil admitted to the cylinders by the transfer valve.

Components of Present Inertial Guidance Systems

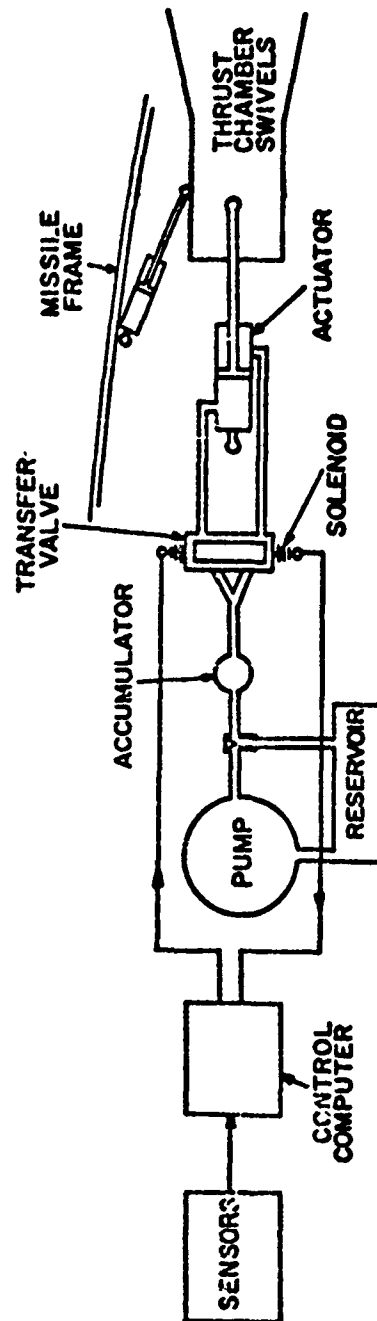


Figure 25. Electrohydraulic Actuator System

Chapter 3

GUIDANCE SYSTEM OF PRESENT DAY MISSILES

Inertial systems are used for the guidance of IRBMs, ICBMs, and satellite launchers. Some of the weapons systems which depend entirely on inertial guidance are the REDSTONE, JUPITER, PERSHING and THOR. The principal characteristics which make inertial guidance suitable for these missiles are:

1. Reliability and Accuracy - The self-contained inertial guidance systems can guide a missile accurately to the desired target
2. Minimum of Ground Support Equipment
3. Immunity to Jamming - Because the guidance system does not depend on electronic signals from the ground, it cannot be jammed by the enemy.

The various inertial guidance systems used on these missiles are discussed in the following sections.

JUPITER SYSTEM

The JUPITER is an IRBM with a range of approximately 1500 miles. Its inertial guidance, based on the Delta-minimum principle, is used to keep the missile as close as possible to the precalculated trajectory. In many respects the JUPITER guidance system could be considered as a refinement of the second V-2 system, but with tremendous improvements in accuracy, stability and reliability.

The JUPITER's inertial guidance is a three-dimensional, modified null-seeking system which continuously compares actual flight path information with precalculated trajectory data. By comparison of the two sets of data, the system senses errors and corrects them by swivelling the engine. The system also provides thrust cut-off and other control signals as required.

Inertial guidance in the JUPITER is based on a space-fixed reference system having three mutually perpendicular axes, each with an associated computer. The gyro-stabilized platform used in the JUPITER is a smaller, lighter and more rugged version of the REDSTONE platform. The platform with its associated components is illustrated in Figure 18.

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The principal components of the stabilized platform are:

1. A stabilized outer ring which provides a space-fixed reference base for the sensing elements
2. Three air-bearing gyros which sense disturbing torques and maintain the attitude of the stabilized ring
3. Two air-bearing pendulums used to establish local horizontal for initial platform alignment
4. Three air-bearing accelerometers used to sense accelerations of the missile in each of three planes
5. A missile mounting bar, caging plate and ring, and remotely operated caging mechanism.

The internal gimbal suspension is illustrated in Figure 19. It differs from previous designs in which the gimbal rings were outside the stabilized parts. The ball-bearing-mounted suspension in the center of the platform saves weight and provides ready access to sensing components for ease in calibration. The missile can move with respect to the stabilized ring. The innermost gimbal allows movement around the yaw axis; the next gimbal, around the roll axis. The platform can move around the pitch axis, which allows sufficient freedom for the tilt program. Yaw, roll, and pitch servo motors provide torques to correct platform disturbances sensed by the three gyros.

Pickoff devices, mounted along the three gimbal axes, sense missile attitude deviations, which are sent through three computers for transmission to control devices. These computers are the altitude computer, range computer, and the cross-range computer. The altitude computer nulls any displacement or velocity errors along its axis by pitch control. The cross-range computer aids by providing the yaw control signals. The range computer determines the thrust cut-off point by solving a simple equation which indicates when the missile has reached the right velocity and position to reach the target. Because the thrust decay of the main engine cannot be accurately predicted, cut-off consists of two steps: (1) main engine cut-off, and (2) vernier engine cut-off.

Prior to launch, the stabilized platform is aligned with the local horizon by means of two air-bearing pendulums which sense the local plumb-line. A bias setting is added to the air-bearing pendulum signal to correct for the earth's rotation. This slaves the platform to an earth-fixed axis until the moment of lift-off. After launch, the pendulums and earth rotation bias are disconnected and the platform is kept space-fixed by the three gyros and servo loops.

Guidance Systems of Present-Day Missiles

Platform azimuth orientation is checked by optical means. A prism is mounted on the stabilized ring and a window provided in the missile skin so that the stabilized platform can be aligned with the ground theodolite. After erection of the missile, the launcher and platform are rotated until the theodolite cross-hairs coincide with their reflected image on the prism. Once the platform has been oriented, it is slaved to the theodolite by azimuth signals provided automatically by an autotheodolite. When the missile is launched, these signals are stopped.

In order to take care of wind disturbances during the ascending portion of the trajectory, an angle-of-attack meter is used to sense the direction of the resultant air flow. Signals from this meter are mixed in the computers which provide corrective pitch and yaw signals and cause the missile to head into the wind, thus preventing the development of excessive angles of attack. The angle-of-attack meter is used only while the missile is passing through the high dynamic pressure region.

REDSTONE AND PERSHING SYSTEMS

The inertial guidance systems used on the REDSTONE and PERSHING missiles are similar to that used on the JUPITER, but their components differ in number, size, construction and accuracy. The REDSTONE system is heavier, bulkier, and less accurate than that of the JUPITER. The PERSHING system is much smaller and lighter than the JUPITER system.

SYSTEMS USED FOR EXPLORER LAUNCHINGS

The inertial guidance system used for EXPLORER satellite launching vehicles is composed of components of the REDSTONE and JUPITER systems. The gyroscopic platform used for EXPLORER launchings is illustrated in Figure 26.

During the booster phase, the missile attitude is controlled by a modified autopilot system. This consists of two free gyros complete with gimbals, control potentiometers, current transfer assemblies, a program transmitter, pendulums, servos, and mounting parts. The pitch gyro providing the signals for pitch control and tilt programming is, for accuracy reasons, supported on air bearings. A yaw-roll gyro senses the yaw and roll of the missile. The control potentiometers sense the position deviations of the gyro elements, and signal the missile controls to make the corrections required to maintain the desired flight path.

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The missile trajectory is also controlled by electrical signals generated in an integrating gyro accelerometer and timer, for ejection of the upper stages.

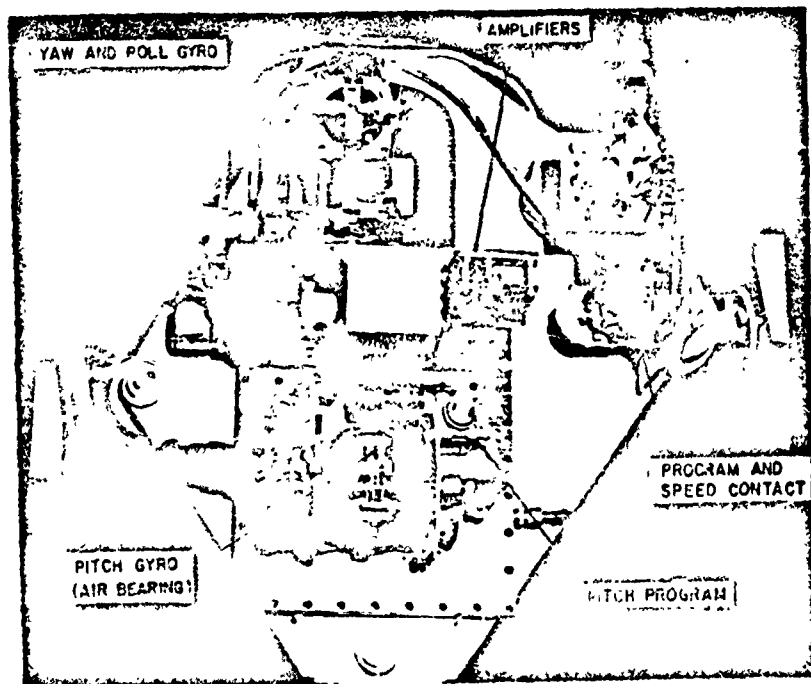


Figure 26. Stabilizing System Used for Explorer Launchings

STABILIZED PLATFORM FOR A RAMJET MISSILE

Inertial guidance systems are also used on some ramjet missiles. Guidance problems with this type of missile are greater than with an IRBM or ICBM because the flight time over the same distance is much longer. Large guidance errors may occur, and the ordinary space-fixed platform used in ballistic missiles is inadequate. A transformation of space-fixed measured accelerations into the earth-fixed system is complicated and difficult to achieve. The use of an earth-fixed system alone also presents serious problems. Precession of the gyros with respect to the rotation of the earth requires such a high degree of accuracy that this approach is considered impractical.

Guidance Systems of Present-Day Missiles

A practical solution to the problem is a combination of the space and earth-fixed reference systems. Orientation and arrangement of the space and earth-fixed parts is such that only a minimum of computations are required. The composite platform for ramjet missiles, built around the internal gimbal system, is shown in Figure 27.

The space-fixed gyros and the earth-fixed accelerometers are mounted on the stabilized platform. The platform is oriented so that its innermost axis, which coincides with the pitch axis of the missile, is always parallel to the guidance plane axis. The position of the guidance plane is determined by the trajectory relative to the rotating earth and the center of the earth, consequently, it is earth-fixed.

The earth-fixed accelerometers are rotated around an axis parallel to the guidance plane axis. The angle of rotation (Figure 28) is determined by the instantaneous position of the missile. This angle is initially set at the launching point and is changed during flight by means of a motor driven by the distance output of the range accelerometer and computer.

The space-fixed gyro part has two additional degrees of freedom. One axis is parallel to the line from the intersection equator-guidance plane circle to the center of the earth. The initial angle setting for this axis, α , (Figure 28) is a constant for a particular flight. It represents the angle between the guidance plane and the meridian plane. The second axis of the space-fixed gyro is kept parallel to the axis of the earth.

The inertial guidance system uses the accelerometers to perform two basic measurements, one of distance and one of orienting the platform in horizontal position. The accelerometers are mounted on the platform with their measuring planes parallel to the surface of the earth. One measures in the flight direction and the other, lateral to the flight direction. Both accelerometers directly integrate the accelerations, which means that one of them measures the distance covered. This value is also used by a motor to rotate the accelerometers in the guidance plane axis according to angle β (Figure 28). The second gives the lateral deviations from the precalculated course. These deviations are reduced to zero by missile control.

The value of earth rotation is introduced into the system by a clock on the earth axis or by a synchronous motor. After setting the proper initial values of α and β the stabilizer is aligned and maintained until launch. At the moment of lift-off, the clock on the earth axis starts and the alignment signals cease.

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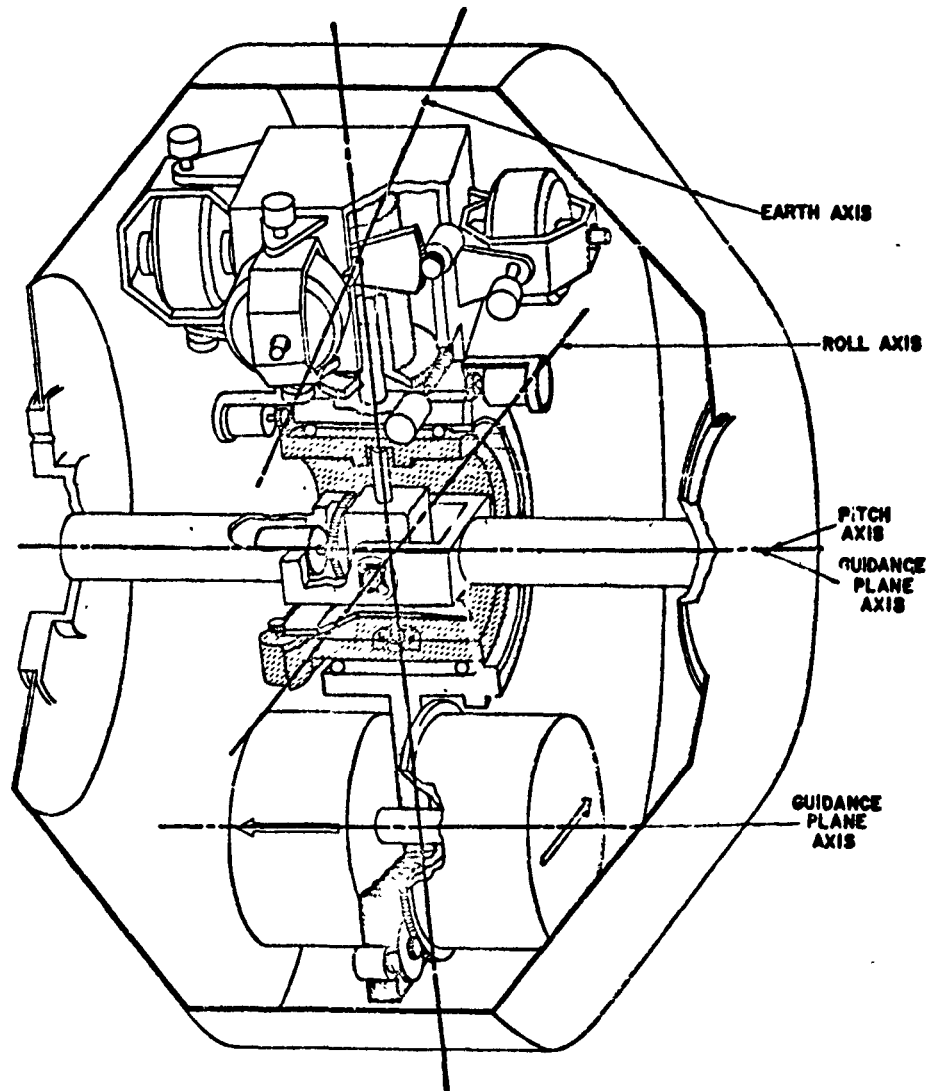


Figure 27. Stabilized Platform for Ramjet Missiles

Guidance Systems of Present-Day Missiles

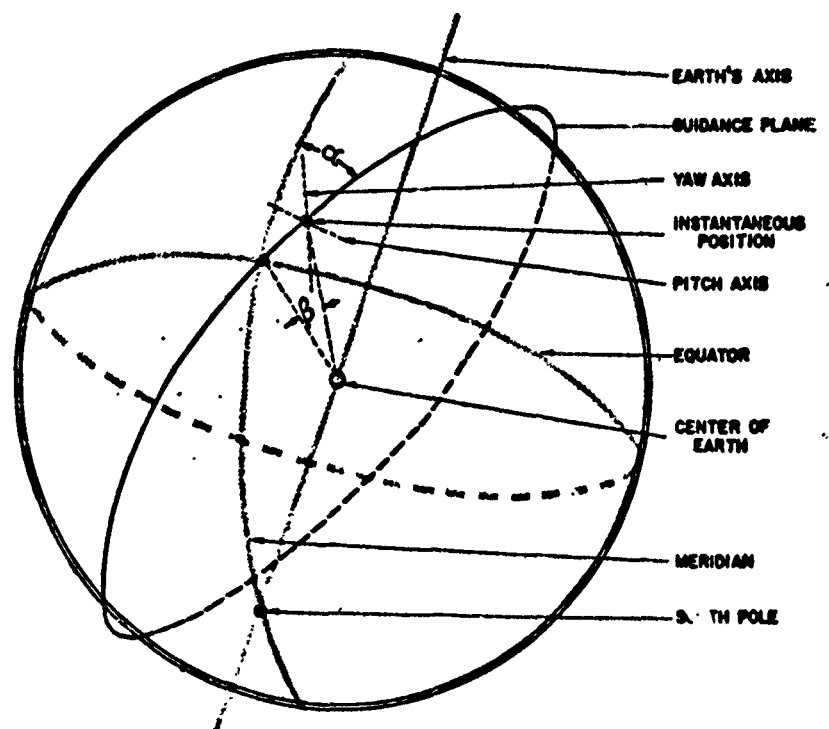


Figure 28. Earth-fixed Coordinate System

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FUTURE OUTLOOK

Since inertial guidance is so successfully used in the ballistic missiles of today, it is highly probable that it will continue to be used in the ballistic missiles of the future. Improvement efforts presently in progress at various development centers will result in even more accurate and more reliable systems. Miniaturization relating to all components, including wiring and cabling, will produce much lighter and smaller systems with reduced power consumption. Applications of new materials such as beryllium and fiberglass, etc., will contribute considerably to weight saving.

There is no doubt that inertial guidance will also play an important part in space travel even if its particular role is not seen clearly today. Interplanetary travel will involve long flight times, but propulsion and correction maneuvers will be executed only during relatively short periods, and the usual guidance errors will be experienced. Consequently, during most of the flight time the errors contributed by guidance will be very small, caused only by minute disturbing effects and friction. Air-bearing guidance components, for example, could be operated as closed self-sustained systems with such low differential pressures that friction and disturbance torques would be negligible.

Further developments will be aimed towards improving the performance of guidance components during the propulsion periods. For example, cryogenic gyros could feature absolutely homogenous bodies and thus eliminate the main shortcoming of a gyro, the shift of balance. The development of electronic gyros and accelerometers is also aimed in this direction.

Beyond these considerations, it should not be forgotten that space travel, especially manned space flight, will permit supervision and correction of inertial systems by celestial tracking.

In view of the above, while it cannot be predicted today how inertial guidance will be applied, it is certain that it will play a major role in the coming space travel.

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