NASA TECHNICAL MEMORANDUM

NASA TM X-52399

GPO PRICE $ ______

CSFTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

NASA TM X-52399

FACILITY FORM 602

N68-21238 (ACCESSION NUMBER) (THRU)

24 (PAGES) 1 (CODE)

TMX-52399 (NASA CR OR TMX OR AD NUMBER) 21 (CATEGORY)

EXPLORING IN AEROSPACE ROCKETRY
12. INERTIAL GUIDANCE SYSTEMS

by Daniel J. Shramo
Lewis Research Center
Cleveland, Ohio

Presented to Lewis Aerospace Explorers
Cleveland, Ohio
1966-67

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

EXPLORING IN AEROSPACE ROCKETRY

12. INERTIAL GUIDANCE SYSTEMS

Daniel J. Shramo

Presented to Lewis Aerospace Explorers
Cleveland, Ohio
1966-67

Advisor, James F. Connors

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

12. INERTIAL GUIDANCE SYSTEMS

Daniel J. Shramo*

NAVIGATION

The ancient navigation problem is one of determining the position of a moving vehicle. This problem can be extended into knowing the position of the destination, which also may be moving, and then comparing the present position of the vehicle with that of the destination to provide steering signal information. But the heart of the problem is the constant knowledge of the present position of the vehicle. Inertial navigation is one of the most recent solutions. Pilotage and celestial navigation are classic methods still very much in use. Pilotage is simply looking for familiar landmarks or features that can be identified on charts. Celestial navigation is based on the fact that at a given instant of time, the observed positions of the stars are unique for any point on Earth. Recently, various electronic aids have been developed to simplify the navigation problem. Some electronic aids, such as loran and shoran, are based on phase relations between signals received from two or more ground stations; others, like omnirange or VOR, are based on the unique phase relation of two signals from one station. Radar on the vehicle itself can reproduce an image of the terrain which can be interpreted as in pilotage.

All navigation systems, except the inertial navigation systems, have one feature in common: that is, the vehicle must collect external information - visual or electronic - to determine its present position. The uniqueness of inertial navigation is that it is self-contained and needs no external information. Once it has been given an initial orientation, the inertial system senses only the motion of the vehicle and navigates by calculating the change in position. This independence is increasingly important in vehicles that must operate in all kinds of weather or away from ground radio transmitters and at speeds which may ionize the surrounding air and interfere with radio transmission. Because of inertial navigation, ballistic missiles, satellites, and spacecraft can now be designed to operate anywhere.

---

*Chief, Guidance and Flight Control Branch, Centaur Project Office.

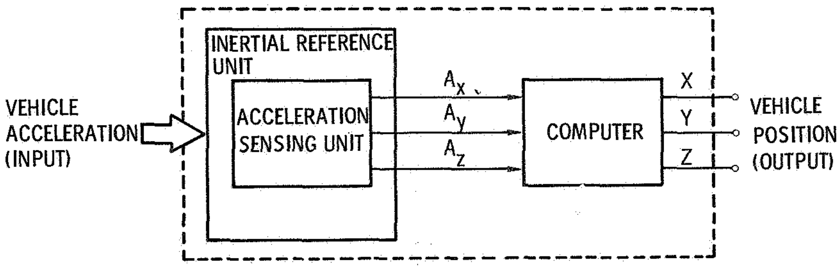


Figure 12-1. - Basic inertial navigation system.

INERTIAL NAVIGATION SYSTEM

The basic inertial navigation system can be thought of as a system whose orientation is fixed, whose input is a physical acceleration (i.e., a rate of change of velocity), and whose output is the vehicle's present position (fig. 12-1). This process of converting acceleration to position requires three major components: the inertial reference unit, the acceleration sensing unit, and the computing unit.

INERTIAL REFERENCE UNIT

The function of the inertial reference unit is always to maintain a fixed orientation regardless of the direction in which the carrier vehicle is moving. Like a compass needle, the inertial reference unit always "points north," but it differs from a compass in that it does not need a lump of magnetic material to tell it where "north" is. Moreover, unlike a compass needle, the inertial reference unit must remain fixed in three directions - "north-south, east-west, and up-down." These directions are seldom those of the compass, so they may be called the x, y, and z axes of the reference system. However, since the inertial reference unit can maintain orientation in any reference system, it is generally desirable to select a system that has at least one visible reference point, such as a star.

No matter what is happening to the vehicle, the inertial reference unit must always maintain its fixed orientation. This is achieved first by mounting a platform so that it is completely free to move, and second, by adding gyroscopes to keep the platform orientation constant.

Gimbals

Gimbals are simply a series of rings of diminishing sizes which are mounted one

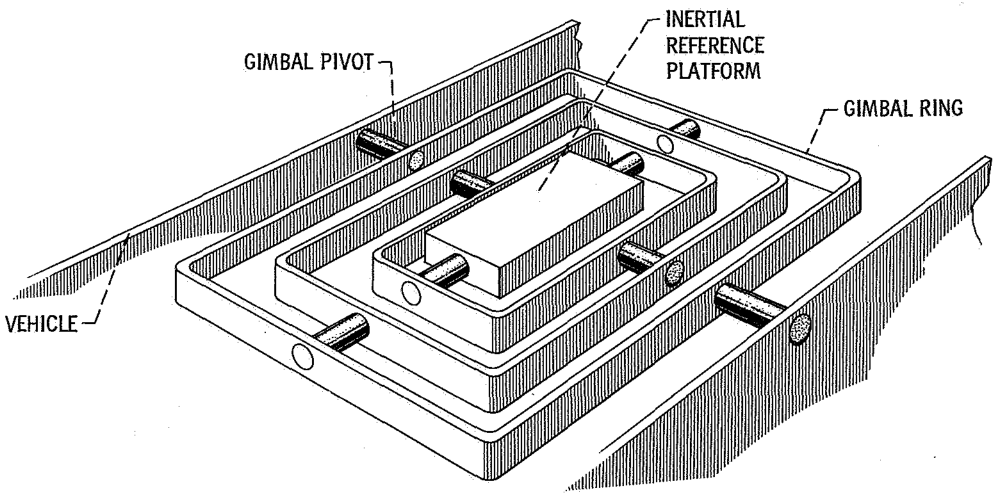


Figure 12-2. - Inertial reference platform mounted on gimbals in vehicle.

inside the other on pivots. The pivots, located 90° apart, allow each ring to rotate independently. The most freedom of motion is achieved with four rings that can move freely about their pivots. Mounted on the last, inside ring, or replacing it, is the inertial platform, which must maintain the fixed orientation (fig. 12-2).

Gyroscope

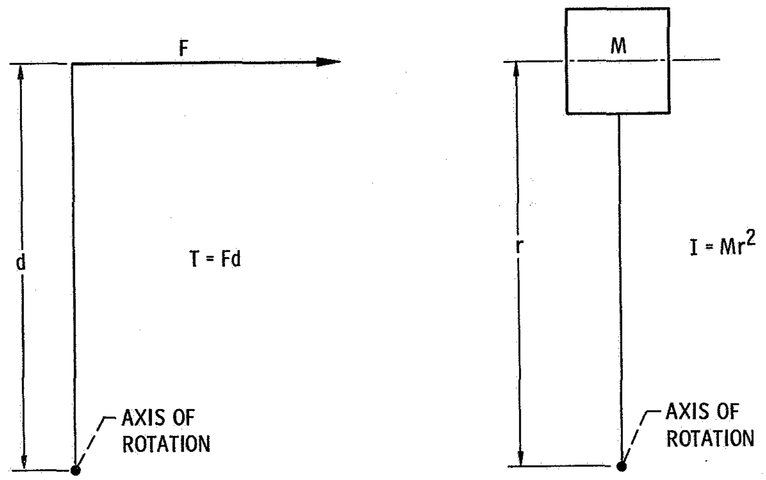
Gyroscopes keep the inertial platform oriented independently of the motion of the vehicle. They provide the stable reference axes for the rest of the system. Since there are three, mutually perpendicular axes (x, y, and z), there must be one gyroscope mounted along each of them. However, since all gyroscopes operate in the same way, only one needs to be discussed here.

Any discussion of the behavior of a gyroscope necessitates the use of certain terms which must be clearly understood. These terms are torque, moment of inertia, couple, and input turning rate. These terms are illustrated in figure 12-3.

Torque. - Torque T is the common measure of the effectiveness of a twisting force acting on a body. This effectiveness is measured by the product of the force F and the perpendicular distance d from the line of action of the force to the axis of rotation.

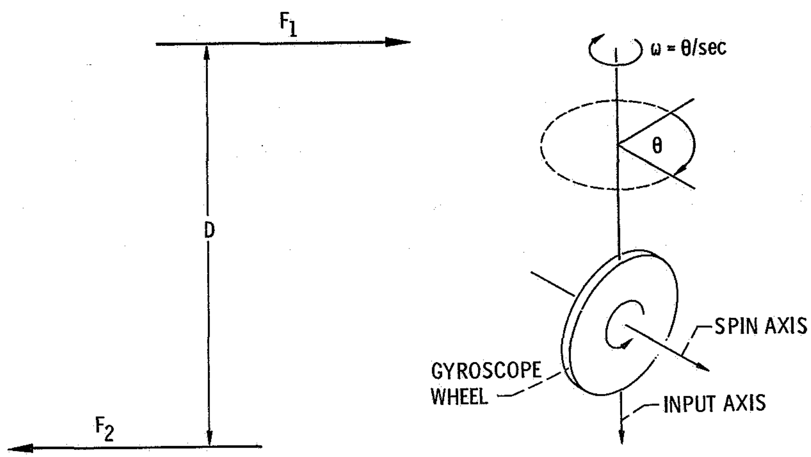
Moment of inertia. - This is a measure of the resistance offered by a body to angular acceleration. The moment of inertia I of a body about a turning axis is the product of the mass M of the body and the square of the distance r from the mass to the axis of rotation.

Couple. - A couple consists of two parallel forces (F_1 and F_2) that are equal in



(a) Torque, T.

(b) Moment of inertia, I.



(c) Couple.

(d) Input turning rate, ω.

Figure 12-3. - Basic terms and concepts.

magnitude but opposite in direction and whose lines of action do not coincide. The sole effect of a couple is to produce rotation. The resultant torque produced by a couple is equal to the product of either of the forces constituting the couple and the perpendicular distance D between their lines of action. This product is called the moment of the couple. The moment of a couple is the same about all axes perpendicular to the plane of the forces constituting the couple.

Input turning rate. - Input turning rate ω is a measure of the response of a point or body to a torque. To allow a comparison of the effects of the same torque on bodies of different sizes, the turning rate is often expressed in angular degrees per second, or radians per second (1 radian = 57.3°).

A useful characteristic of a gyroscope is that a turning rate about its input axis causes a torque about its output axis (these two axes are perpendicular to each other).

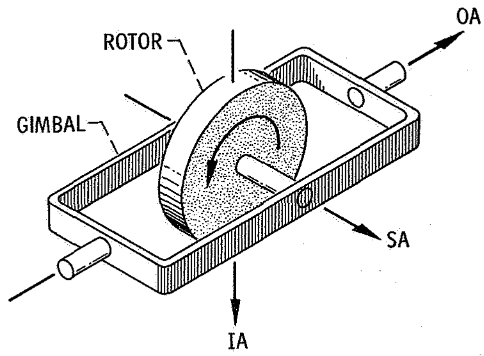


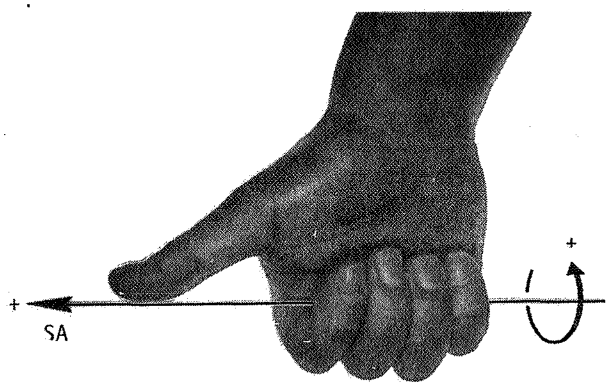
Figure 12-4. - Gyroscope reference axes.

The three axes of a gyroscope are shown in figure 12-4, where SA is the spin axis, IA is the angular turning rate input axis, and OA is the gyroscope gimbal torque output axis. (Note that these gyroscope axes are not the same as the orientation axes.) The interrelation of the three axes is such that if the positive end of SA is rotated towards the positive end of IA, the positive direction of OA is determined by the "right-hand rule." This rule is a common method of designating a sign convention (either positive or negative) for the direction of rotation about an axis and for the relative directions of the three mutually perpendicular axes of a gyroscope.

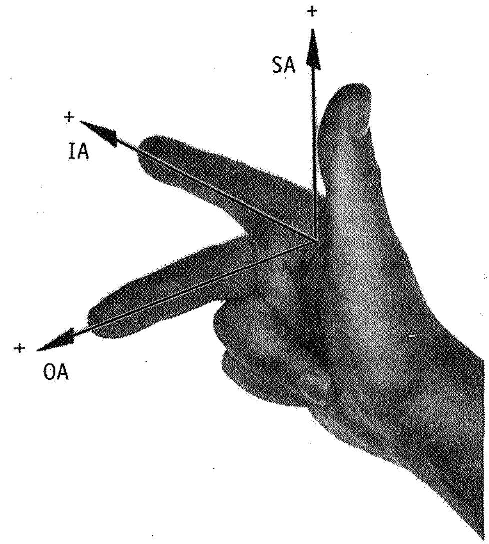
One form of the right-hand rule is used to determine the direction of rotation about an axis relative to the direction of that axis (fig. 12-5(a)). For example, assume that the thumb of the right hand lies along the spin axis of the gyroscope wheel and that the thumb is pointing in the positive direction along this axis. Then, the positive direction of rotation about this spin axis is the direction in which the fingers of the right hand point as they curl around the line (or axis) formed by the thumb. Obviously, this rule can also be used in reverse; that is, if the positive direction of rotation about an axis is known, then this rule can be used to determine the positive direction of the axis.

Another form of the right-hand rule can be used to determine the relative directions of three mutually perpendicular axes (fig. 12-5(b)). In this application, assume that the right thumb pointing upward indicates the positive direction of a single axis. Then, the positive direction of a second axis can be indicated by the index finger pointing forward so that it is perpendicular to, and in the same plane as, the thumb. The positive direction of a third axis can be indicated by the middle finger pointing in such a way that it is perpendicular to the plane of the thumb and index finger. Thus, if the thumb, the index finger, and the middle finger of the right hand are used to represent the three axes of a gyroscope, the relative positive (or negative) directions of these axes are the directions in which the fingers are pointing.

The right-hand rule can be used to describe the behavior of a gyroscope. Assume that the spin axis is the thumb, the input axis is the index finger, and the output axis is



(a) Determining direction of rotation relative to direction of axis.



(b) Determining relative directions of three mutually perpendicular axes.

Figure 12-5. - Applications of right-hand rule.

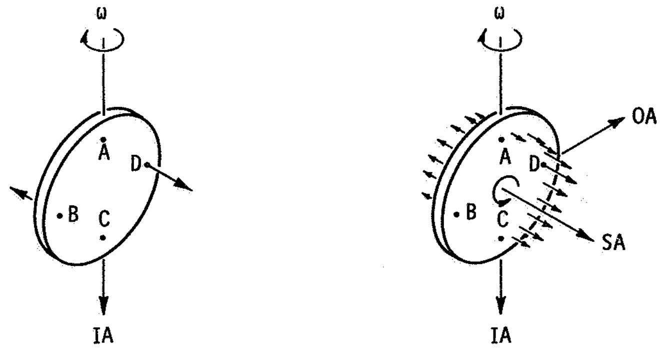
the middle finger. Also assume that the gyroscope wheel is spinning about the spin axis (thumb) in the positive direction according to the right-hand rule. Now, if positive rotation (according to the right-hand rule) is initiated about the input axis (index finger), the gyroscope will rotate about the output axis (middle finger) in the positive direction according to the right-hand rule.

Some practice with the right-hand rule can be of considerable help in the understanding of the sign conventions and of the operation of a gyroscope.

The gyroscopic torque or precession phenomenon should be understood before gyro performance characteristics are considered. In a nonspinning disk which is turning about an axis that lies along a diameter of the disk, as shown in figure 12-6(a), the masses at points A and C lying along the input axis have no velocity; however, the masses at points B and D at 90° to the input axis have maximum velocity and are opposite in direction.

Now if the disk is set in rotation about the spin axis normal to the surface of the disk (fig. 12-6(b)), the input turning rate ω causes no rim velocity to the mass at point A. But since this mass is moving towards point B, it must accelerate to maximum velocity by the time it reaches there, and then it must decelerate to zero velocity again at point C. At point C, the mass must reverse direction and begin to accelerate. At point D, the mass has attained maximum opposite velocity and must begin to decelerate again.

A force is required to change the direction or the velocity of any mass ($F = ma$). Therefore, a force is required to accelerate the mass from the instant it leaves point D,



(a) Nonspinning disk.

(b) Spinning disk.

Figure 12-6. - Particle on disk that is turning about axis that lies along its diameter.

passing through A, until it reaches point B. An opposite force acts on the mass as it leaves point B, passes through C, and reaches point D. These two forces form a couple which produces a torque about the BD axis. Thus, any attempt to rotate a gyro about an axis at right angles to a spin axis causes a torque about an axis at right angles to both the input axis and the spin axis. This torque T at 90° to the input axis is proportional to the spin rate Ω, the moment of inertia of the disk about its spin axis I, and the input turning rate ω; so that $T = I\Omega\omega$. Since most gyros are designed for a constant spin rate, the moment of inertia and the spin rate are more often combined into a constant angular momentum H, where $H = I\Omega$, and the torque equation becomes $T = H\omega$. The input can be either a torque or a turning rate causing either a turning rate or torque output.

To convert a spinning wheel into a useful device, the wheel is mounted in a single gimbal so that the output axis is perpendicular to the wheel spin axis. This is a single-degree-of-freedom gyro, shown in figure 12-7. The remaining axis, which is perpendicular to both the output and spin axes, is the input or sensitive axis. This is the axis that must be parallel to one of the orientation axes. For the right-hand rule, the axes go in alphabetical order: input, output, and spin. The input axis is the axis around which the turning rate or angle is measured and is the stable reference axis that the gyro provides for the inertial navigation system. The signal which gives information is obtained from the resulting motion of the gimbal about the output axis relative to the frame.

When a simple gyro is mechanized for use in an inertial guidance system, several additional elements are added to the basic gyro (fig. 12-8). One of the elements is a damper around the output axis. The second element is a signal generator which senses the rotation of the gyro output axis. The third element is a torque generator which supplies torque to the output axis of the gyro. A simple gyro with these additional elements is shown incorporated into a single-axis platform stabilization scheme in

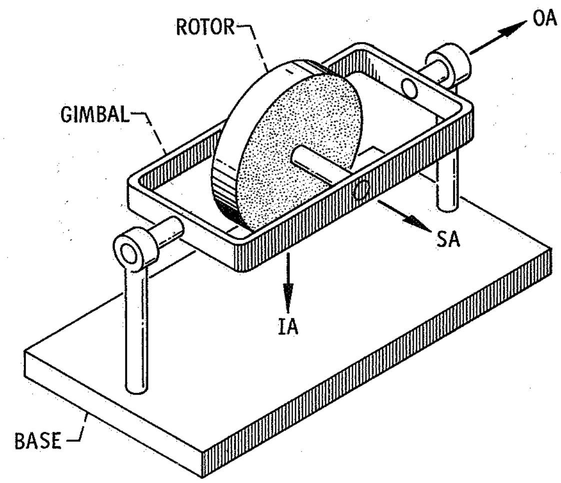


Figure 12-7. - Gyroscope with single degree of freedom.

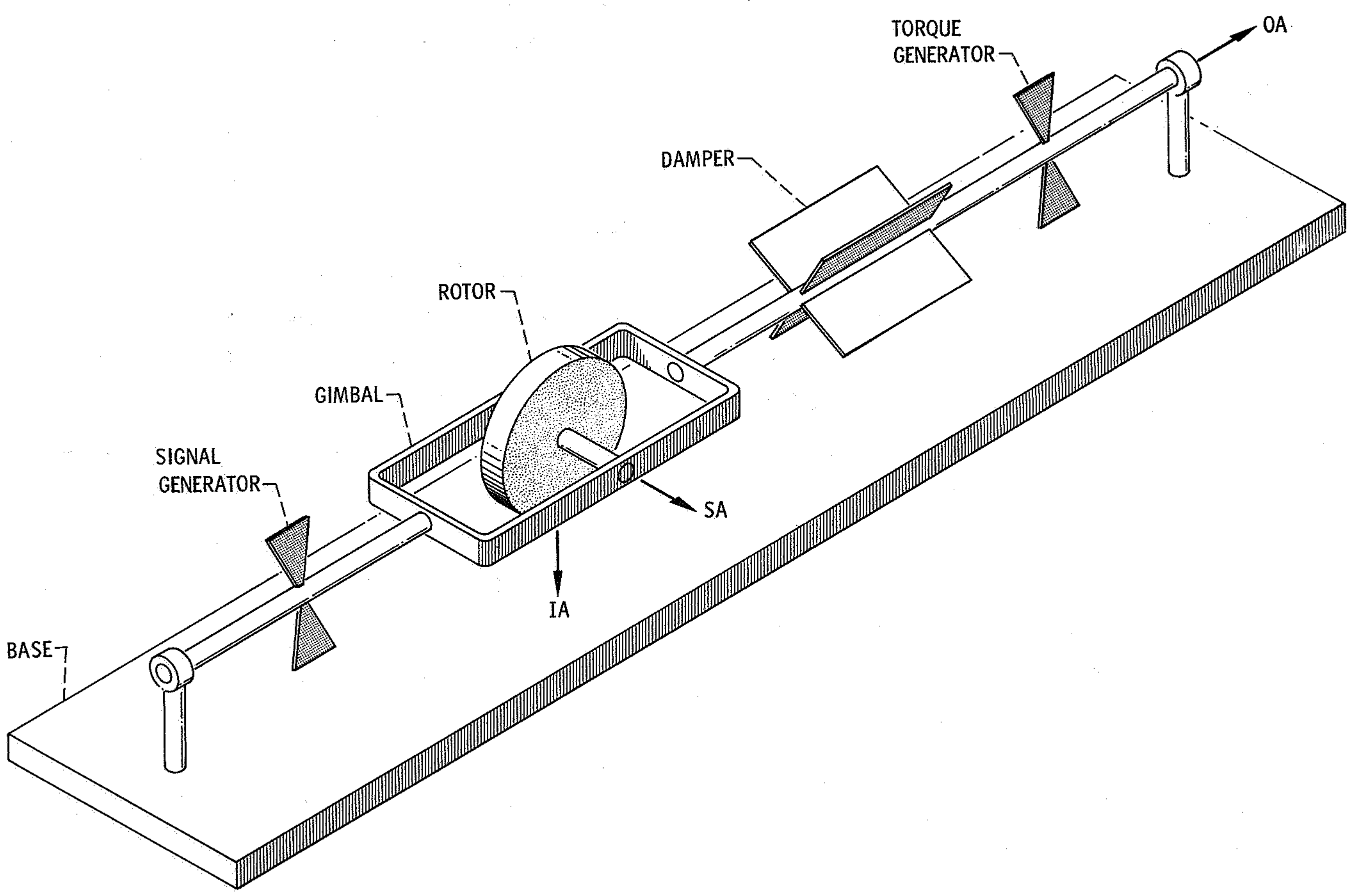


Figure 12-8. - Inertial gyroscope mechanization.

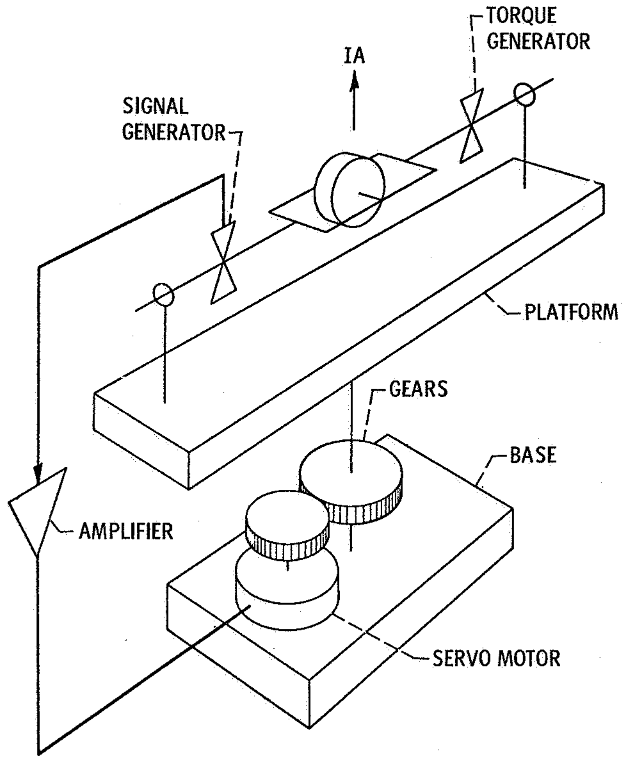


Figure 12-9. - Single-axis platform stabilization.

figure 12-9. Information from the signal generator is used by the servomotor to keep the platform oriented, while the torque generator is used to correct errors in the gyro and to calibrate it (to be discussed later). In the single-axis representation of the platform-mounted gyro shown in figure 12-9, any rotation of the platform about the gyro input axis will be sensed by the signal generator, amplified, and then used to drive the servomotor to return the platform to the initial orientation.

Examples of gyroscopic behavior are common in everyday life. For instance, an ordinary hand power drill is much more awkward to wave around at random when it is running than when it is not. More scientifically, an ordinary power drill can be used to observe the responses of a gyroscope. If the electric motor is considered the spinning mass of the gyro, its axis is the spin axis SA; the pistol-grip handle of the drill is then the input axis. Now, hold the drill by its grip and switch it on (note: do <u>not</u> use a bit in the drill). While it is running, point the drill at a spot on the wall. By using only wrist action, swing the drill 90° to the right; then repeat the procedure to the left. Notice that the drill is easier to swing in one direction than in the other; furthermore, in the more difficult direction the handle of the drill is gently pushing against your palm. It is this pushing force that is called precession and is used to maintain the orientation of a gyroscope.

Gyroscopic Drift

The preceding explanation of the behavior of a gyroscope assumed that the gyroscope was functioning ideally. Unfortunately, this assumption seldom holds true. A gyroscope seldom maintains an exact orientation for long because many small forces that are present due to magnetism, friction, mass unbalance, etc. cannot be eliminated and because the gyroscope is so sensitive. The shifting of a gyroscope away from its assigned orientation is called drift.

The two categories of drift are (1) constant drift, and (2) drifts that are proportional to acceleration forces. Constant drift is caused by small forces that are constantly present and are of fixed magnitude. The drifts that are proportional to acceleration are caused by net mass unbalances along the spin axis and along the input axis. When these unbalanced masses are subjected to acceleration forces, they cause a rotation about the output axis (fig. 12-10). This rotation is an equivalent gyroscopic drift.

Within each of the two categories of drift there is a portion that is predictable and a portion that is random. There are two methods of correcting for predictable drift. One method is to apply an electrical signal to the torque generator to cause a rotation about the output axis that will counteract the effects of the predictable drifts. The other method is to allow the gyroscope to drift and to add (or subtract) a correction factor to (or from) the information supplied by the gyroscope. Predictable drift in an inertial gyroscope is only about 2° per hour. Random drift is more difficult to control. Since the exact magnitude and direction of this drift are unknown, no mechanical or mathematical correction is possible. About the only effective approach to this problem is to seek and to reduce its causes. This has already been done to such an extent that for a typical inertial-grade gyroscope the error due to random drift is only about 0.05° per hour (or approximately $1\frac{1}{4}^{\circ}$ per day).

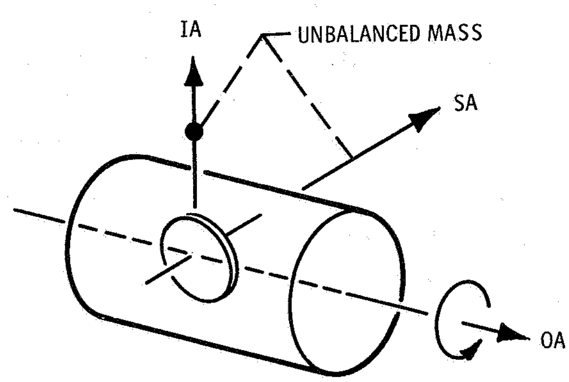


Figure 12-10.- Gyroscope mass unbalance. (Accelerations along either IA or SA will cause torque about OA due to mass unbalance.)

ACCELERATION SENSING UNIT

The acceleration sensing unit is mounted on the inertial reference unit. Its function is to sense change in the velocity of the vehicle. It is important to understand that the sensing unit cannot measure velocity alone; that is, it cannot sense that the vehicle is moving so many miles per hour. All that it can sense is the change in velocity--if the vehicle's velocity changes from 0 to 20 feet per second, that rate of change, the acceleration, is all that is sensed. If the change in velocity took place in 1 second, then the sensor would note an acceleration of 20 feet per second per second. Just as the inertial reference unit must remain oriented in the x, y, and z directions, the acceleration sensing unit must respond to changes in velocity in all three directions; it follows that the acceleration sensing unit can then also respond to changes that occur between the axes, such as in an xy direction.

If it is mounted on the constantly oriented inertial reference unit, the acceleration sensing unit is constantly oriented too. The job of the acceleration sensing unit is more complex than that of the inertial reference unit because the three axes represent six directions. The acceleration sensing unit must indicate not only the existence of an acceleration along a particular axis, but also the direction of that acceleration. Moreover, the acceleration sensing unit must also be able to indicate the amount of the acceleration. Fortunately, there is a device which can measure both the direction and magnitude of a force; this device is an accelerometer. Three accelerometers are needed, one for each axis. But since the three accelerometers are similar in operation and differ only in orientation, only one needs explaining.

The function of the accelerometer is simply to sense linear physical accelerations and to provide a proportional electrical output signal. The term accelerometer is also in common use for certain types of vibration pickups, but the linear accelerometer is the one of principal interest in inertial navigation. The basic accelerometer may be thought of as a damped, spring-restrained mass whose displacement is proportional to acceleration. However, for various design reasons the rotation equivalent of a damped spring-restrained pendulum is more commonly used. Figure 12-11 is a diagram of this type of accelerometer. The axis about which the pendulum rotates is called the output axis OA. The pendulous axis PA is the arbitrary neutral position of the pendulum. The input axis IA is the sensitive axis of the accelerometer and is perpendicular to both the output axis and the pendulous axis. The determination of a positive direction of acceleration is such that OA rotated into IA by the right-hand rule equals PA. The pendulous accelerometer may be thought of as a torque-summing device. The steady-state torque equation is

$$pa = K\varphi + F$$

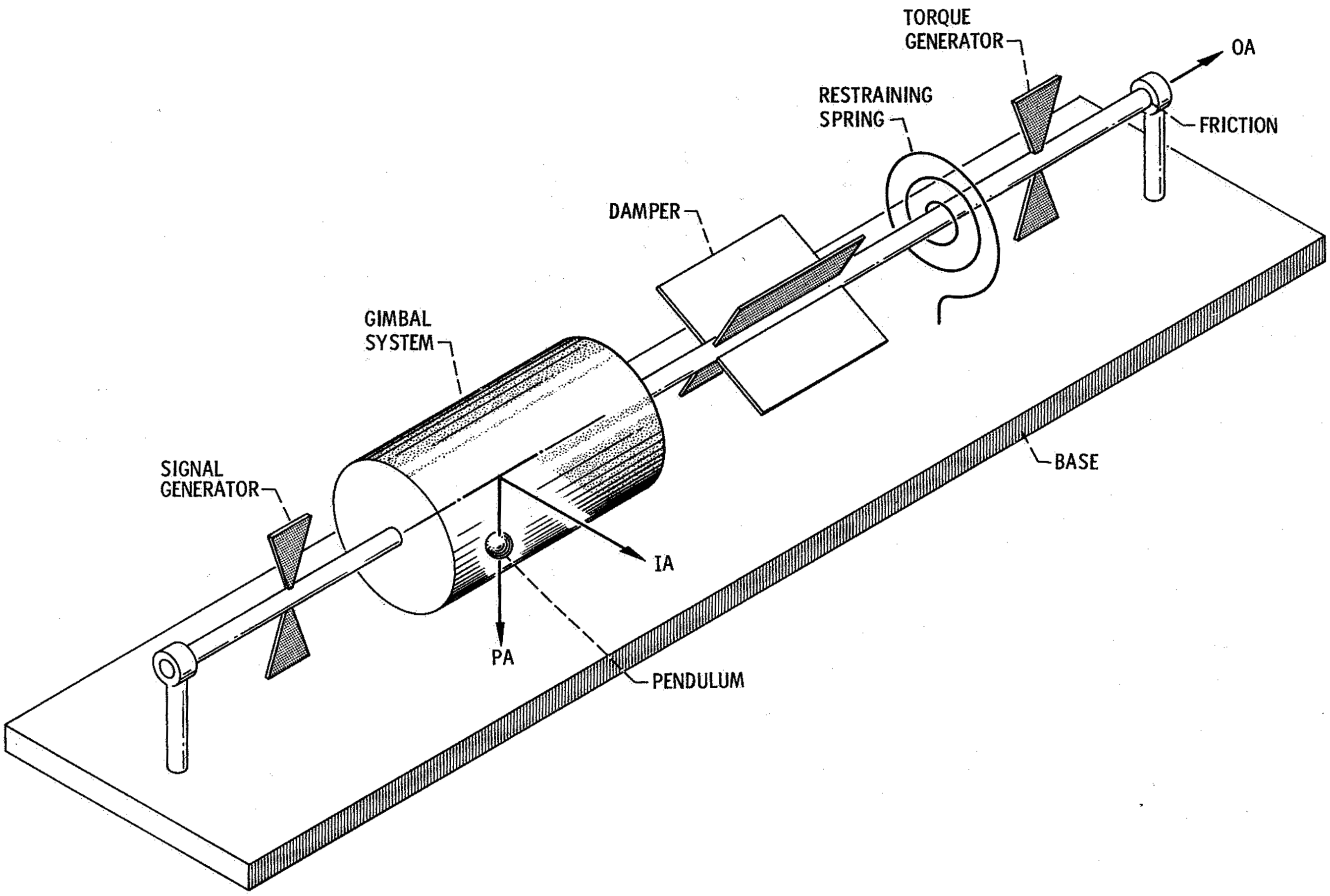


Figure 12-11. - Functional diagram of basic pendulous accelerometer.

where

p pendulosity (the pendulum mass multiplied by its distance from the point of rotation)

a linear acceleration acting perpendicular to the output axis and the pendulous axis

K constant (the spring rate of the restraining springs)

φ angular displacement of the pendulum

F friction in the system

If K and p are constant and F is negligible, the equation resolves to

$$a = \varphi\left(\frac{K}{p}\right)$$

and the displacement of the pendulum is then directly proportional to the acceleration measured.

Generally, the pendulous accelerometer does not have a mechanical spring but derives its spring restraint from closed loop operation of an electrical circuit. In most applications the output motion φ resulting from an input acceleration is sensed by a moving coil signal generator. This signal is sent to an electronic circuit which determines the magnitude and the direction (+ or -) of the motion (i. e., if the +y direction were designated as north, then the -y direction would be south). The accelerometer also contains two opposing torquing coils through which an electrical signal can be used to force the pendulum in one direction or the other. The electrical signal derived from the signal generator output is channeled to the proper torquing coil and the accelerometer pendulum is moved in a direction to match exactly the input acceleration, thereby keeping the pendulum at the center position. The electrical rebalance signal is a direct measure of the input acceleration and is used by the computing unit.

The accelerometer has a number of significant parameters whose stabilities determine the accuracy of its performance in an inertial guidance system. These parameters are scale factor, threshold, null uncertainty, and bias. The current in the torquer is proportional to the measured acceleration. Accelerometer scale factor is the current required to balance out a given acceleration input divided by that input acceleration. The smallest acceleration input which causes a detectable output is the threshold. In inertial applications, a threshold of less than 1×10^{-6} g is common. When the acceleration input to an accelerometer is changed from a positive to a negative number of the same value, the exact location of the output null or zero reading should be repeatable to within 5×10^{-5} g. The nonrepeatability is called the null uncertainty. The bias of an accelerometer is the output reading that the accelerometer gives when it is sensing zero gravity. Zero gravity can be simulated on the Earth's surface by orienting the accelerometer so that the input axis is at right angles to the Earth's gravity field. With the input axis of the accelerometer perpendicular to the Earth's gravity field, the accelerometer should indicate a zero output. The actual reading is the accelerometer bias. In addition to the accelerometer parameters discussed here, a number of secondary parameters that influence accelerometer performance are also present. Among these are cross-coupling effects and vibration effects. These are discussed in the references 1 and 2, and an understanding of them is not required for a basic discussion of inertial navigation systems.

Because accelerometer parameters are variable, they cannot be measured exactly, and so these parameters become the primary sources of error when such an accelerometer is used in an inertial navigation system. However, the combined error or uncertainty of all the parameters is extremely small. The method of calibration of an accelerometer is relatively simple and is discussed in reference 2. Inertial accelerometers are designed so that bias and scale factor are the predominant sources of error; therefore, only these parameters need to be measured to ensure accurate system operation.

Typical values for the limits of stability for short durations (approximately 12 hr) are 20 parts per million for the accelerometer scale factor and 40 parts per million for the accelerometer bias.

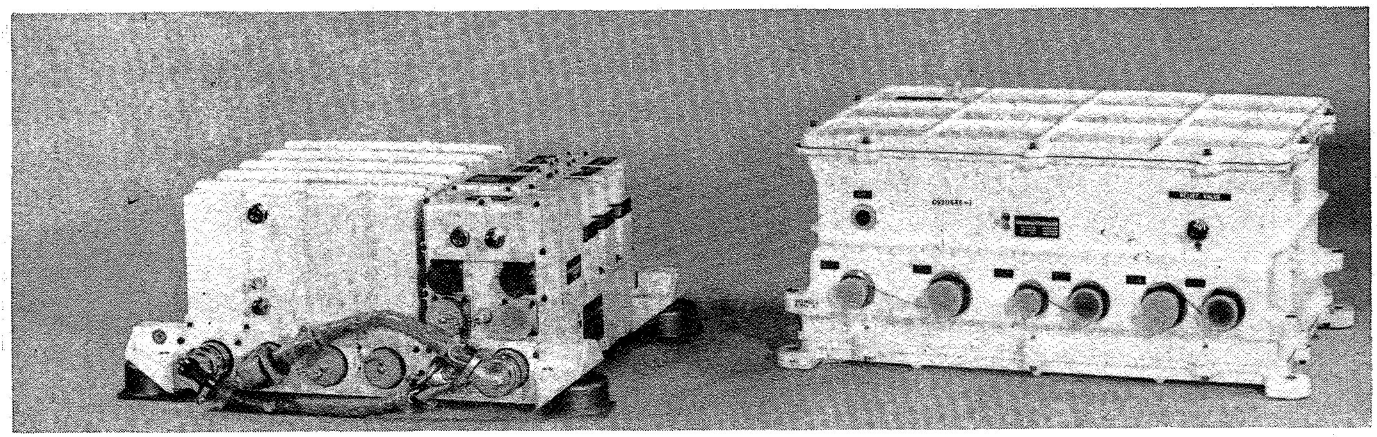
COMPUTING UNIT

Signals from the acceleration sensing unit are sent on to the computing unit where the accelerations are converted to the distance and direction information that is needed to determine the vehicle position. The computing unit converts accelerations to distance by integrating the electrical acceleration signals. Direction of travel is determined from the relative activity of each sensor. For example, if the only acceleration signal the computer receives is from the north end of the "north-south" sensor, then the vehicle is moving north. If the acceleration signals from the north end of the "north-south" sensor and from the west end of the "east-west" sensor are equal in strength, then the vehicle is traveling northwest.

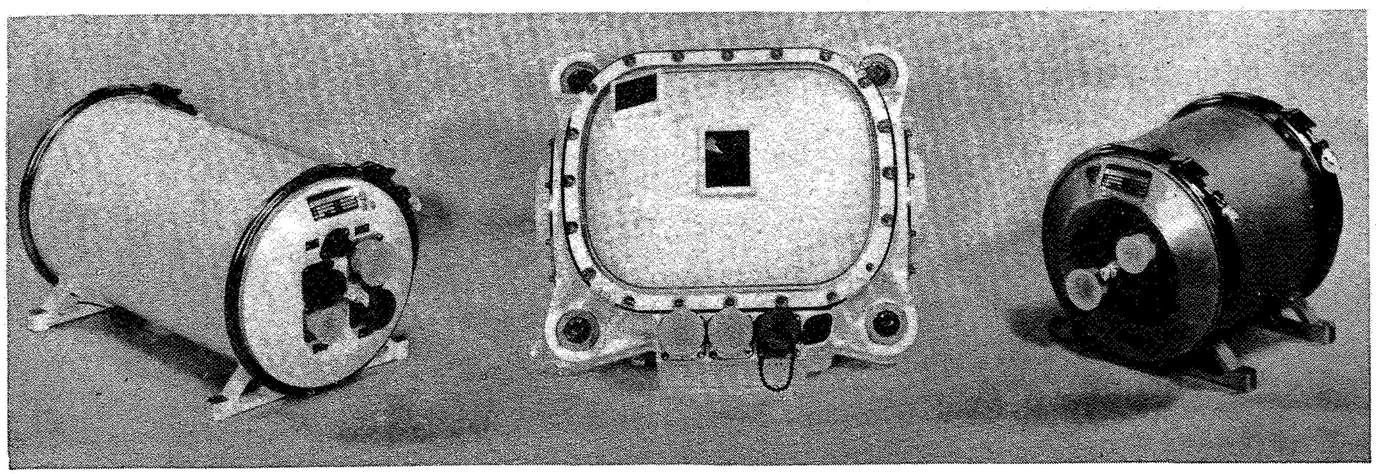
Distance traveled is more difficult to compute since it depends not only on which sensor is responding and the strength of that response but also on the time during which that response takes place. Time is usually measured by sampling the response of the sensors at fixed intervals, perhaps every 1/100 second. For example, let us assume that the first sample indicates an acceleration of 0 feet per second per second from all sensors, that during the next 100 samples the x and y sensors continue to indicate zero acceleration while the z sensor indicates a velocity change of 100 feet per second, and that a final sample indicates that all sensors are again at 0. From this information, the computer can calculate that during the elapsed second the vehicle has increased its velocity by 100 feet per second. The computer adds this velocity increase to the previous velocity calculation. If the sample above was taken during the first second after a launch, the computer would then show that the vehicle had moved 100 feet in the z direction. Since the final indication from the sensors was 0, and if it remains 0, the computer will continue to add 100 feet to the distance traveled for every additional second of flight. Actually, the computer performs these calculations each time it samples the responses of the sensors instead of each second; therefore, its answers are more precise. The information from the computer is used to generate guidance signals to control the vehicle.

CENTAUR GUIDANCE SYSTEM

The Centaur launch vehicle is guided by an inertial navigation system which uses three gyros to orient an inertial platform in a known inertial reference frame, three accelerometers to measure the accelerations along the axes of that frame, and a guidance computer to determine the precise position of the spacecraft and thus generate steering signals so that the vehicle will inject its payload into the proper trajectory. Figure 12-12 shows the Centaur guidance system, which comprises five individual units - a miniature inertial platform, its associated platform electronics, a coupler, the digital computer, and the signal generator. Figure 12-13 shows the miniature inertial platform and its relation to the platform electronics and to the coupler. The primary purpose of the Centaur inertial platform is to maintain a fixed reference point in space and to measure the acceleration of the Centaur vehicle. Figure 12-14 shows the platform electronics unit, which receives output signals from the gyros and, in turn, sends electrical signals which cause the platform gimbal motors to counteract any disturbing forces on the gyros. Thus, the platform is maintained in a fixed position with respect to inertial space. Figure 12-15 shows the guidance-system coupler, or accelerometer rebalance electronics and power-supply system. The accelerometer signal-generator output is sent to the coupler where the direction of the disturbance is detected and a new rebalance signal is sent back to the accelerometer such as to bring the accelerometer pendulum to zero or null. These rebalance forces are proportional to the input acceleration, and the electronics are mechanized in such a fashion that positive and negative pulses are sent to the accelerometer to keep it at its balance point. The algebraic sum of the rebalance pulses in any given time period is a measure of the velocity change, or acceleration, during that time period. Figure 12-16 shows the Centaur digital computer. The computer counts the net rebalance pulses sent to each accelerometer. Each pulse represents a change in velocity, or acceleration. The computer mathematically processes the number of pulses per unit of time and determines the direction of flight and speed of the rocket vehicle. This information is compared to similar information permanently stored in the computer memory. The computer generates steering signals for the rocket autopilot to reduce the difference between information stored in the computer and the actual speed and direction of the vehicle in flight. The final item in the Centaur inertial guidance system is the signal conditioner (fig. 12-17). Although the signal conditioner is not required to perform an inertial navigation task, it is important on scientific flights. The signal conditioner receives samples of important guidance-system electrical signals. When necessary, it converts these to radio signals which are transmitted through the rocket vehicle telemetry system to ground receiving stations. With this flight information received from the signal conditioner, the in-flight performance of the inertial navigation system can be reconstructed by using mathematical formulas and ground computers. Figure 12-18 shows schematically the interrelation of the five components of the total Centaur guidance system.

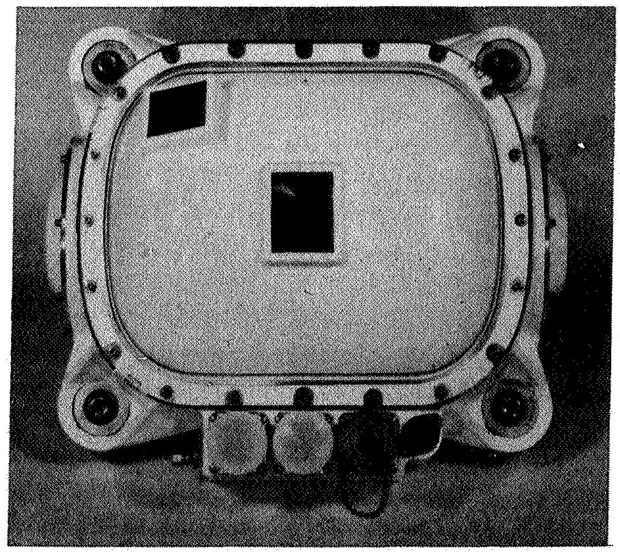


DIGITAL COMPUTER COUPLER



PLATFORM ELECTRONICS MINIATURE INERTIAL PLATFORM SIGNAL CONDITIONER

Figure 12-12. - Centaur guidance system.



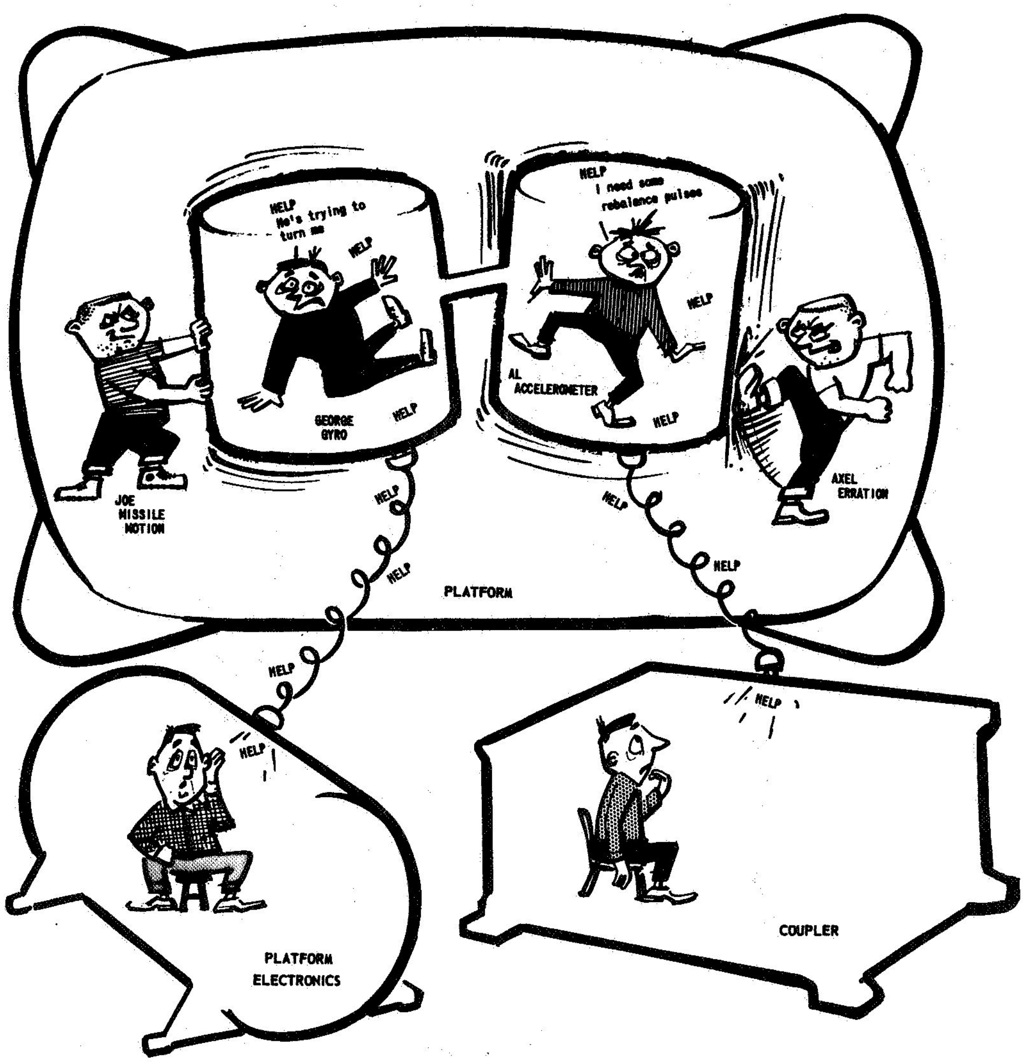


Figure 12-13. - Miniature inertial platform (four-gimbal, all-attitude). Weight, 32 pounds; volume, 0.99 cubic foot.

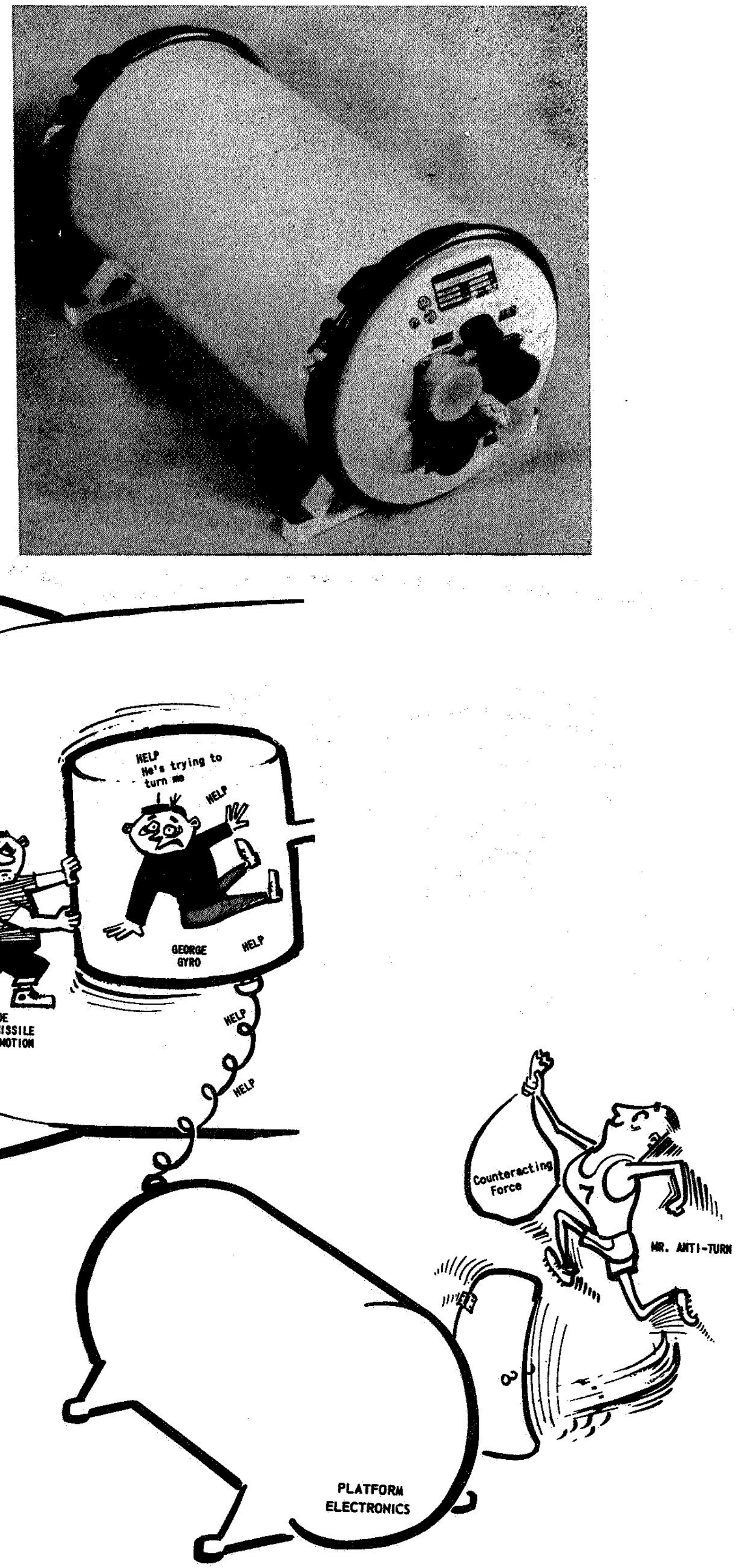
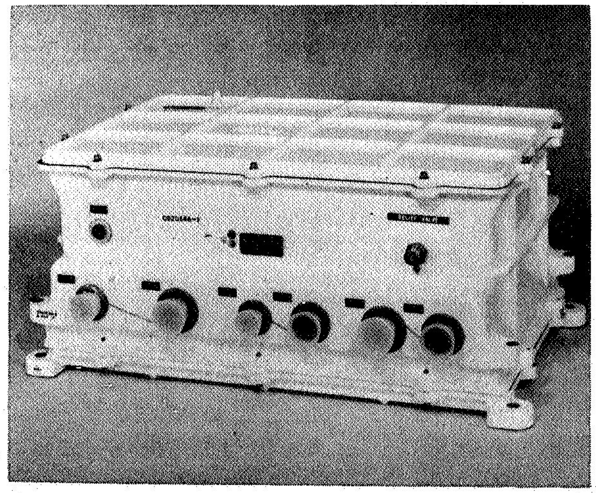


Figure 12-14. - Platform electronics unit. Weight, 18.5 pounds; volume, 0.61 cubic foot.



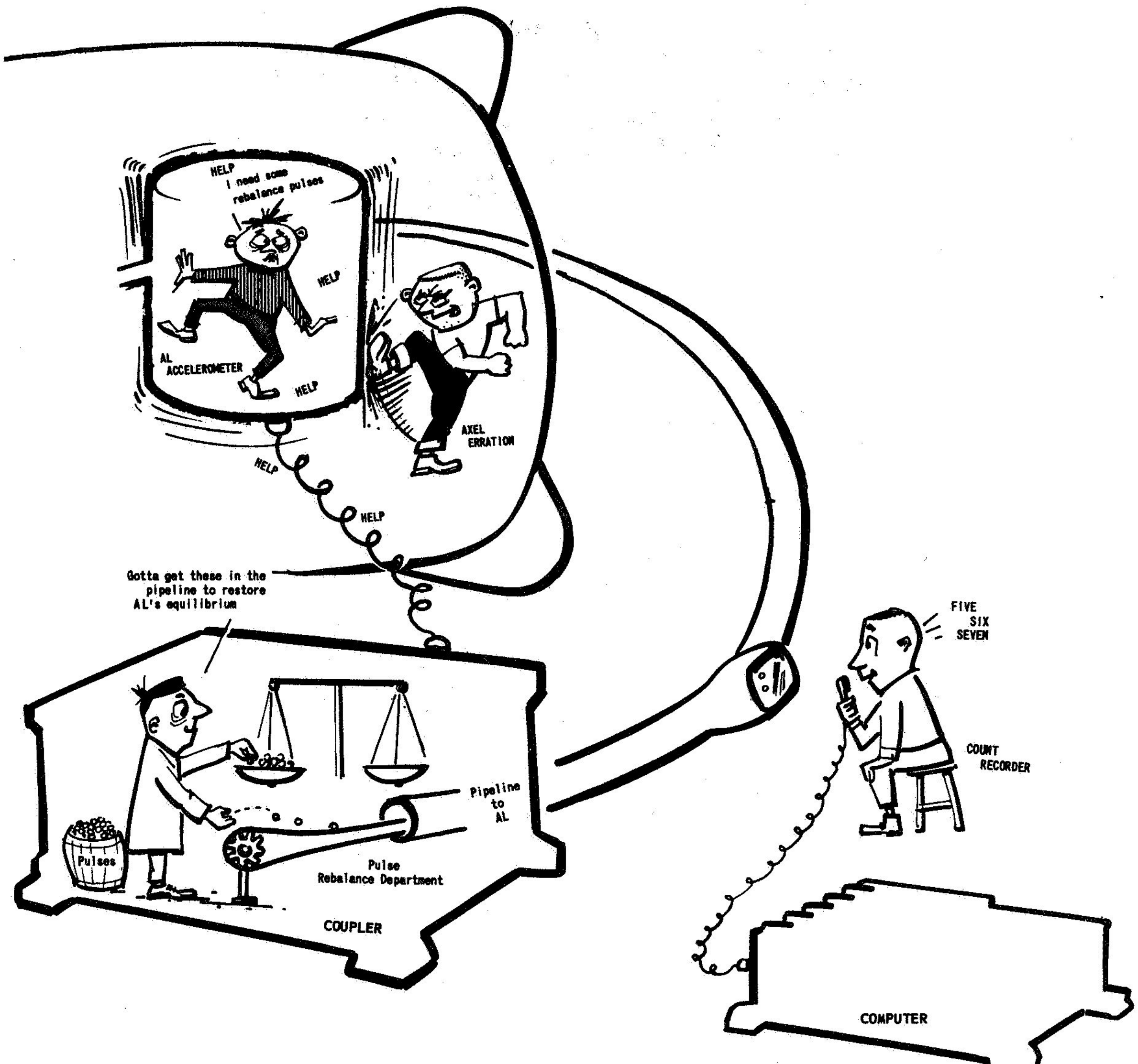
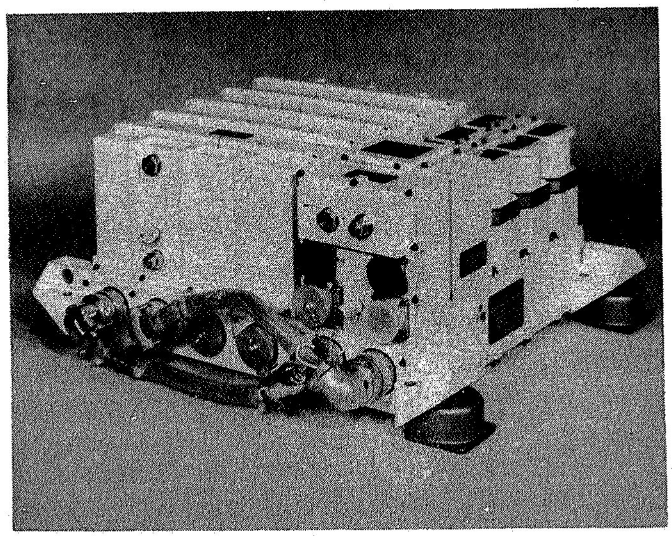


Figure 12-15. - Guidance-system coupler (accelerometer rebalance electronics and system power supplies). Weight, 60 pounds; volume, 1.58 cubic feet.



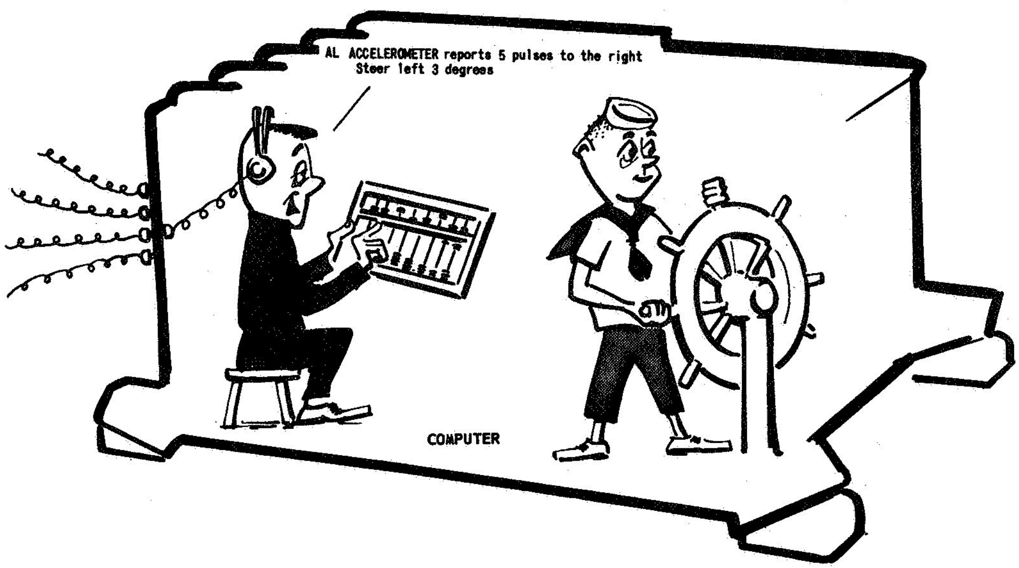
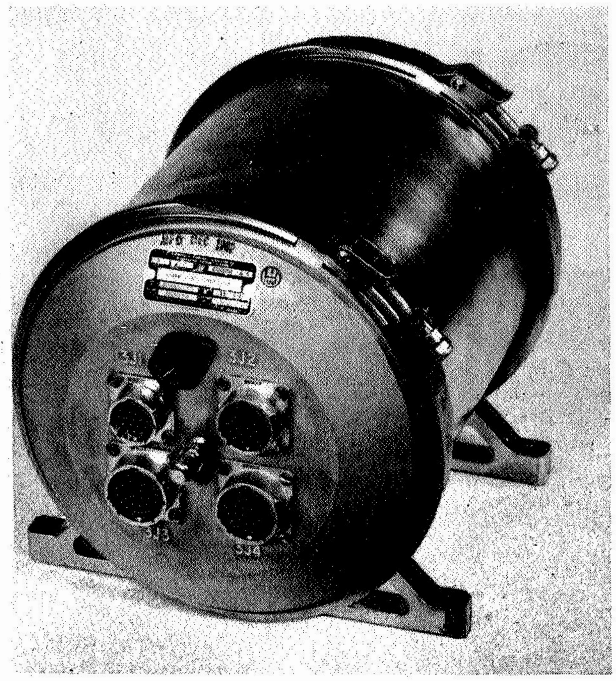


Figure 12-16. - Digital computer (memory unit plus input-output unit). Weight, 65 pounds; volume, 1.46 cubic feet.



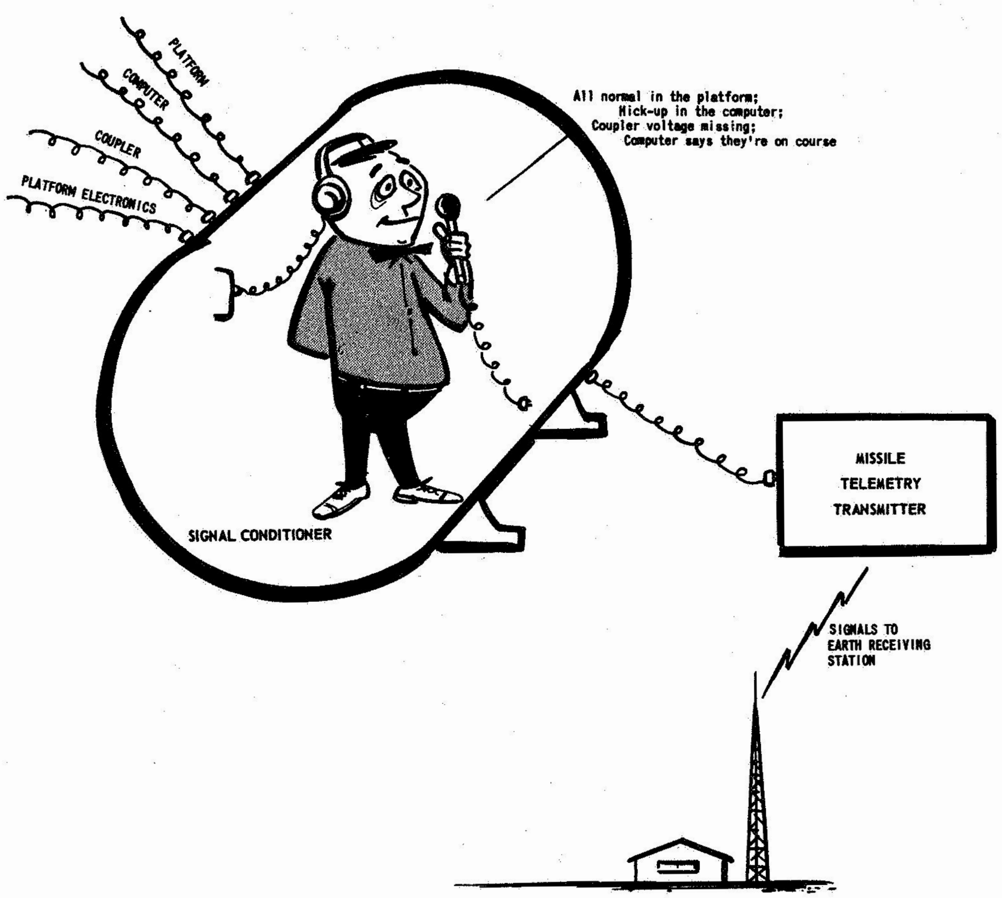


Figure 12-17. - Signal conditioner. Weight, 10 pounds; volume, 0.4 cubic foot.

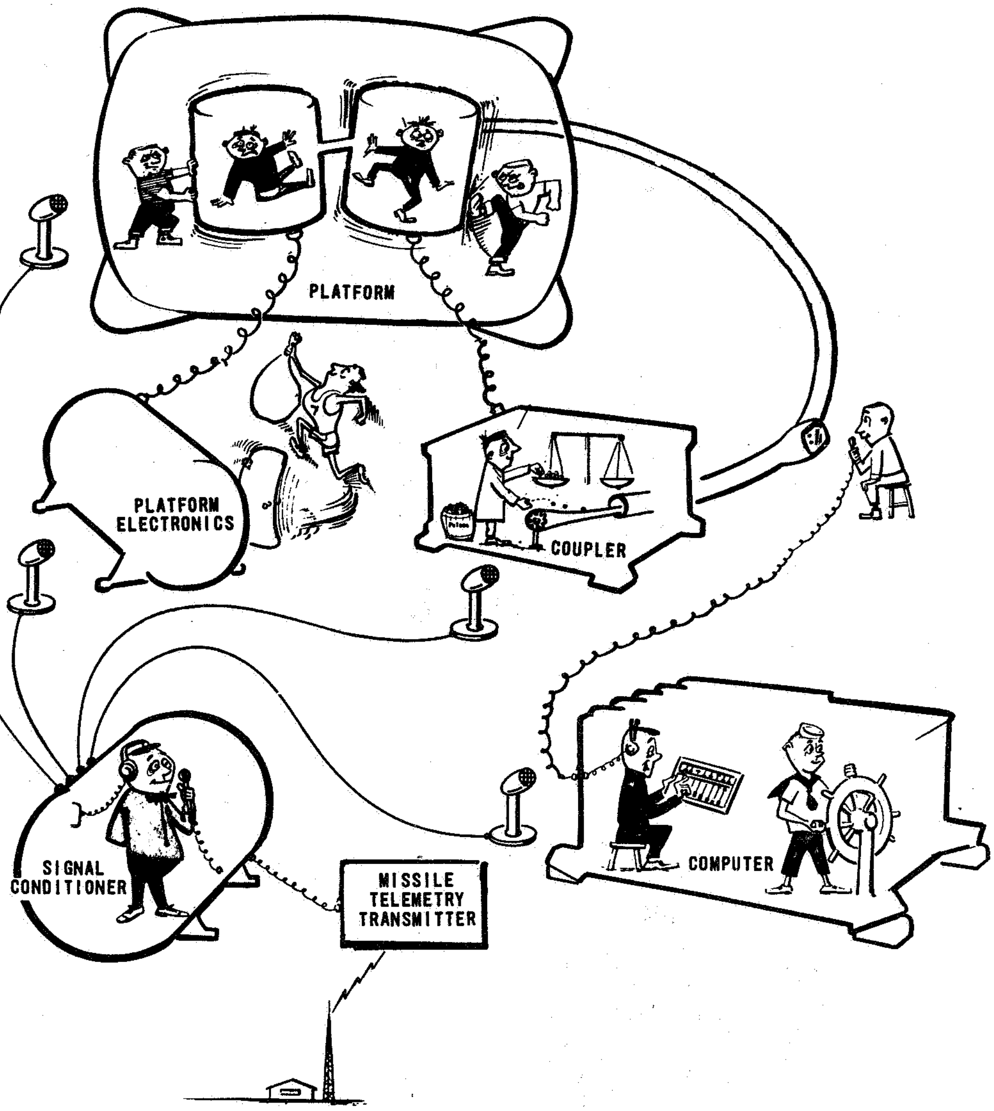


Figure 12-18. - Interrelation of components of Centaur guidance system.

As long-distance air travel increases and as space travel becomes more common, inertial navigation systems will be relied upon more heavily to perform the guidance and navigation functions for these modes of transportation. Since no external information about the route of travel is necessary to perform inertial navigation, the use of inertial navigation systems will be valuable for space exploration and for long-distance flights over remote areas of the Earth where navigation aids are not available.

REFERENCES

1. Pitman, George R., ed.: Inertial Guidance. John Wiley & Sons, Inc., 1962.
2. Parvin, Richard H.: Inertial Navigation. D. Van Nostrand Co., Inc., 1962.

NASA-CLEVELAND, OHIO E-3364-12