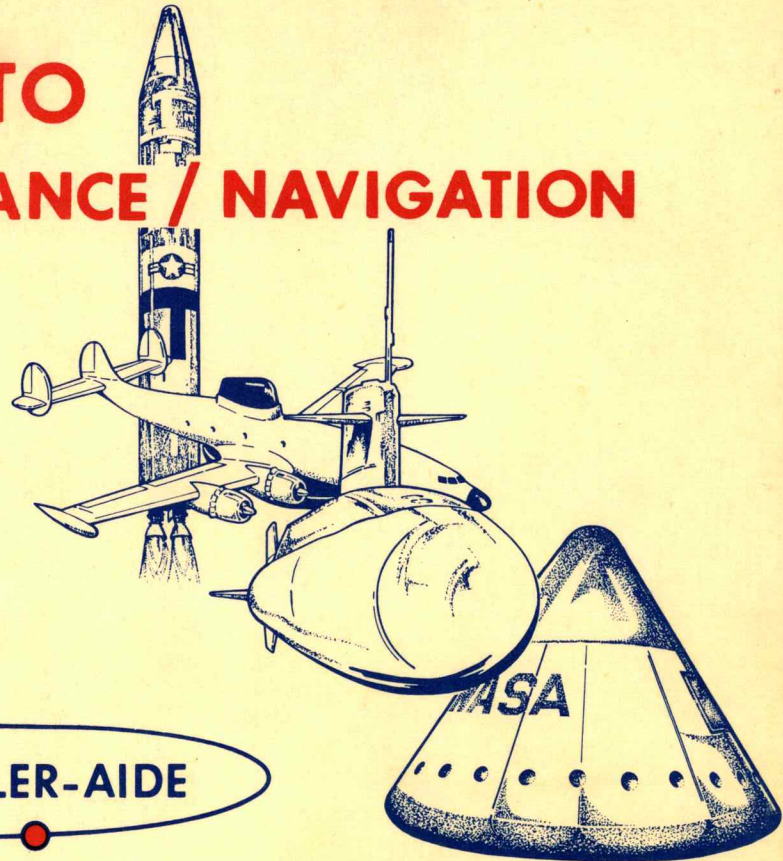
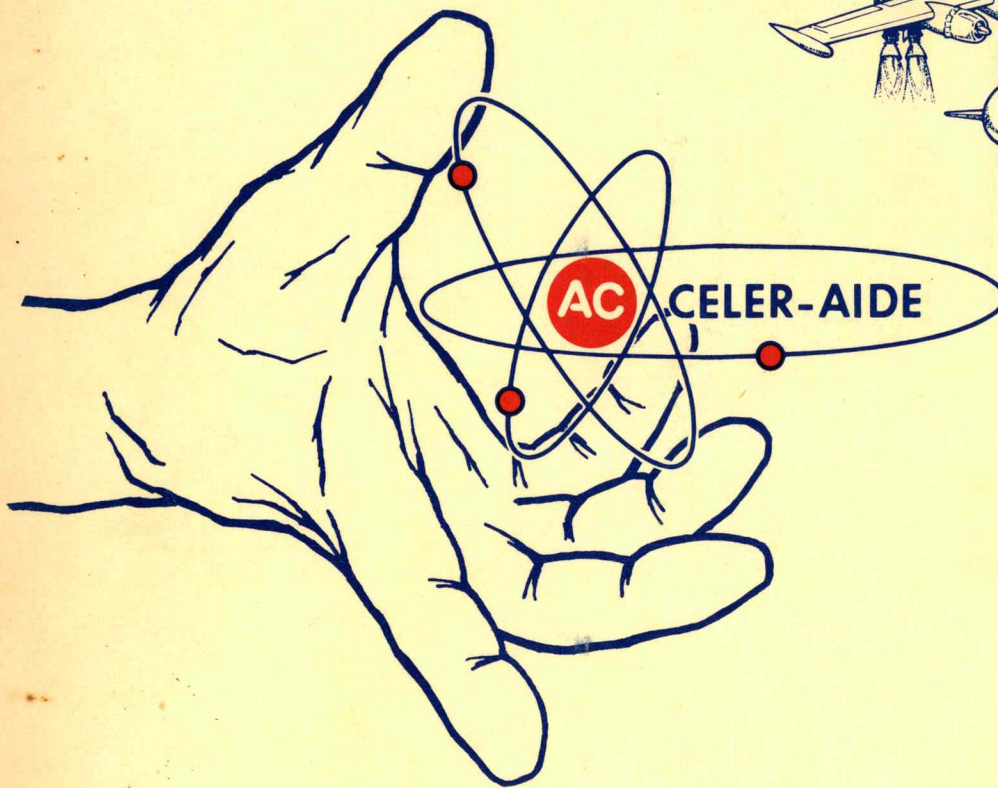


SATREUSEL
INERTIAL INSTRUMENT SERIES...

INTRODUCTION TO GUIDANCE / NAVIGATION



PROGRAMED TRAINING MATERIALS
prepared by: FIELD SERVICE TRAINING
AC SPARK PLUG DIVISION OF GMC

INTRODUCTION TO GUIDANCE / NAVIGATION

a programed instructional text



General Motors Corporation, 1965

PRELIMINARY

APRIL, 1965

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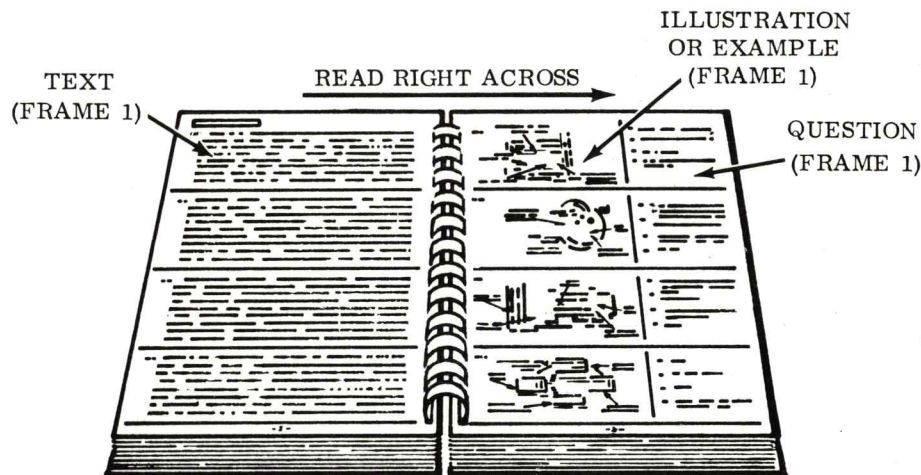
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HOW DOES THIS WORK?

This text has been designed to teach you new materials in a fashion called "programed instruction". After you have read the introduction, you will quickly see that the text is designed quite differently than the normal book. Material has been divided into small increments, illustrations or examples included, and many questions provided for your use. Programed instruction presents materials in logical steps and it requires that you participate to derive full benefit from its use.

HOW DO I USE IT?

This text can be used with an ACceler-aide teaching machine, or by itself. Instructions for use with the machine will be found in the machine. These instructions which follow are for use when you have the text only. When you start through the programed series you will see that the pages are designed as follows:



The book is written in a series of frames separated by dark lines. When you read the material, the procedure to follow is:

1. Read the text material for a particular frame.
2. Next, read or view the illustration or example if there is one. This is located on the opposite page from the text.
3. Read the question in the frame last, then compare your answer with the answer sheet. The answer sheet is a fold-out page at the back of this text.

Note: If at any time an illustration or question is not present, simply continue on to the next item. Should you answer a question incorrectly, then for best results, reread the frame.

REMEMBER THE ORDER: 1) Text 2) Illustration or example 3) Question and verification

Note: On many pages in this text you will see instructions such as:

TURN SELECTOR TO POSITION 1

These are for use with the ACcelerator-aide teaching machine. Disregard these statements when you are using the text with no machine.

NOTE: *(ANSWER SHEET)*

When this text is used with no ACcelerator-aide machine, an answer sheet is found in the back of the text. Simply fold out the answer sheet to expose the correct answers. For best results, cover the answers with paper or a book marker - then expose them after you have made a choice.

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THE PROGRAM BEGINS
ON THE FOLLOWING PAGE.

INTRODUCTION TO GUIDANCE/NAVIGATION

The field of guidance/navigation is one of the oldest precise sciences in existence. Ever since man has existed, he has had to devise some method of determining where he is and how he must proceed to reach his desired goal. In very early years, this was a simple and perhaps instinctive function for man. It was a matter of passing from one familiar landmark to another. It wasn't long, however, until man left land to sail the seas, and his guidance/navigation problem became more complex. He used the stars to assist him in navigating, and to this day man relies on the stars for both earth and space navigation. With the advent of ballistic missiles and space probes, several new guidance/navigation techniques were developed for use in these high speed vehicles. This book, in addition to discussing some of the general background information on guidance/navigation, will specifically present one of these techniques; i. e. , inertial guidance/navigation. The material presented here is designed to introduce you to inertial guidance/navigation so that the study of specific inertial instruments (gyroscopes and accelerometers) will be more meaningful. At the completion of this text, you will not be an expert on inertial guidance, but you should have an understanding of inertial guidance/navigation requirements and basically how these requirements can be fulfilled. Although the time required to complete this text will vary considerably from student to student, it is estimated that this text will take about 8 hours to complete.

TURN SELECTOR TO POSITION 1

(1) NEWTON AND INERTIAL GUIDANCE/NAVIGATION

A text on inertial guidance/navigation is fittingly started with a discussion of Sir Isaac Newton, for he advanced the equations and descriptions of motion which are the basis for inertial guidance.

IMPORTANT

Appendix I of this text is a review of the most important terms which will be used in this text. If you have any difficulty with these terms as you go along, or if you wish to refresh your memory of basic terms before continuing, then proceed to Appendix I. After reading Appendix I return to this point in the program.

-
- (2) Newton was born in 1642. During his 75 years, he discovered or invented many things that are the basis for today's technological advances. Among his discoveries are differential calculus, properties of light and colors, and the binomial theorem.

-
- (3) He was a well educated man, whose technical and scientific expression was somewhat hampered due to timely public opinion and the controversial nature of some of his ideas. In fact, if it had not been for one of his good friends tactfully persuading him to write the "Principia", in spite of its controversial content, it never would have been written.

-
- (4) The "Principia", published in 1686, is one of the most important documents ever written by Newton because it contains his observations and interpretations of the tides, heavens and the motion of objects on earth.

(1)

WE SHALL SEE THAT THE BASIC EQUATIONS OF MOTION DESCRIBED BY
NEWTON MANY YEARS AGO FORM THE BASIS FOR INERTIAL GUIDANCE.

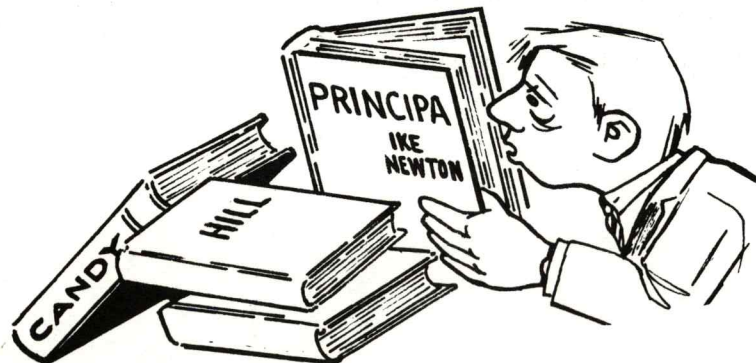
(2)



(3)



(4)



TURN SELECTOR TO POSITION 1

- (5) In the "Principia", Newton documents his, now well known, three laws of motion. These laws form the basis for our entire system of dynamics.

(6) Let's look at each one of these laws and see what they imply.

1. The first law really defines "force" by saying any change in motion is caused by "something"; that "something" is a force. A body at rest tends to stay at rest, a body in motion tends to stay in motion. Only an external force can change these conditions (Inertia).
2. The second law says that the change in momentum of a body is directly proportioned to the impressed force and in the direction of the force. The momentum of a body is mass x velocity, if the momentum is changed then the velocity must have changed. (Mass is constant.) A change in velocity is called acceleration, thus the familiar expression $F = MA$.
3. The third law states that action and reaction are equal and opposite. If a body "A" exerts a force on a body "B", then "B" simultaneously exerts an equal and opposite force on "A". A force may not cause actual motion but always tends to do so.

-
- (7) All three of these laws are very important for the study of motions on earth or in space. There is special significance in Newton's second law for it is this law that has direct application to Inertial Guidance/Navigation Systems.



(6) Newton's three laws:

1. Inertia - A body at rest tends to remain at rest, a body in motion tends to remain in motion unless an external force is applied.
2. $F = MA$
(Force = Mass x Acceleration)
3. Action equals Reaction

Newton's first law dealing with inertia indicates that an external _____ must be applied, for a body to change its present condition of motion.

- A. force
- B. pressure
- C. voltage
- D. none of the above

When the action of the gases expanding in the rifle chamber of a fired weapon cause the reaction of the bullet being propelled, example of Newton's _____ law has been demonstrated.

- A. fourth
- B. first
- C. third
- D. none of the above

(7)

AS WE STUDY INERTIAL GUIDANCE/NAVIGATION WE WILL SEE ALL OF NEWTON'S LAWS APPLY, BUT OFTEN IT WILL BE MOST EVIDENT THAT $F = MA$ IS APPLIED (NEWTON'S SECOND LAW).

Shortly, when we study inertial guidance/navigation, it will be Newton's _____ law which is easily observed.

- A. first
- B. second
- C. third
- D. none of the above

TURN SELECTOR TO POSITION 2

(8) DEFINITION OF INERTIAL GUIDANCE/NAVIGATION

Inertial Guidance/Navigation Systems are really the mechanization of Newton's laws governing motion. The sole purpose of mechanizing these laws is to provide information for navigating from one point to another.

-
- (9) Inertial Guidance/Navigation Systems are used in rockets, missiles, aircraft and submarines. These systems have the unique capability of being able to provide continuous navigation/guidance information without having any command communications from outside the vehicle.

-
- (10) We can summarize by saying, "Inertial Guidance/Navigation Systems are completely self-contained units which rely solely on the mechanization of Newton's laws of motion for required data."

(8)

AS WE STUDY INERTIAL GUIDANCE AND NAVIGATION SYSTEMS, WE WILL SEE NEWTON'S LAWS BEING MECHANIZED FOR THE PRIMARY PURPOSE OF PROVIDING INFORMATION NEEDED TO NAVIGATE FROM ONE POINT TO ANOTHER.

(9)

ONE OF THE BIG ADVANTAGES OF INERTIAL GUIDANCE/NAVIGATION SYSTEMS IS THAT THEY PROVIDE THE NECESSARY INFORMATION WITHOUT RECEIVING SIGNALS WHICH ARE EXTERNAL TO THE VEHICLE.

(10)

INERTIAL GUIDANCE AND/OR NAVIGATION SYSTEMS ARE COMPLETELY SELF - CONTAINED.

One of the biggest advantages of inertial guidance/navigation systems is that they:

- A. are self-contained.
- B. are radio controlled.
- C. need no power.
- D. all of the above.

TURN SELECTOR TO POSITION 3

(11) THE GUIDANCE PROBLEM

We said that Newton's second law was the primary source of concern when referring to Inertial Guidance/Navigation Systems. Let's look at how we can relate this law with the problem to be solved.

The Problem: To have the capability of proceeding from a given point (on earth or in space) to another point (on earth or in space) knowing only the exact position of the start point and the destination.

Considerations:

The two points can be any distance apart.

A vehicle of some kind must carry the Inertial Guidance/Navigation System and must respond to its commands. (The vehicle could be a ship, car, rocket, aircraft or any means of transportation which is capable of reaching the destination.)

The Solution: By mechanizing Newton's second law ($F = MA$) a determination of acceleration can be made. Once acceleration is known, it is a matter of arithmetic manipulation to obtain velocity and distance.

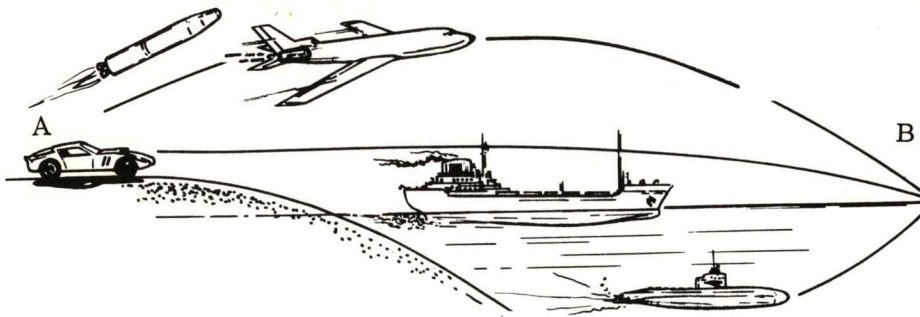
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- (12) It is important that we know certain facts about the Guidance/Navigation problem and its solution in order to do an efficient job. We must know the exact position of the start point and the exact position of the destination.

This information will give us the capability of determining:

- a. The distance to be traveled.
- b. The direction in which to travel.
- c. The approximate time of travel at a given velocity.
- d. The most appropriate route to travel.

-
- (13) Let's assume that we have a device which will measure acceleration. Because it does measure, or meter, acceleration we'll call it an "accelerometer". Within the box is some mechanization of Newton's laws which enable us to determine the acceleration that the accelerometer undergoes.

- (11) THE GUIDANCE PROBLEM BOILS DOWN TO "GETTING FROM A KNOWN POINT" TO "ANOTHER KNOWN POINT".



Mechanizing Newton's law ($F = MA$) we will develop a device which will sense and indicate acceleration. Mathematically, the system will then derive velocity and distance.

The guidance problem basically consists of traveling from:

- A. all of these answers are correct.
- B. land to sea.
- C. land to space to land.
- D. one known point to another known point.

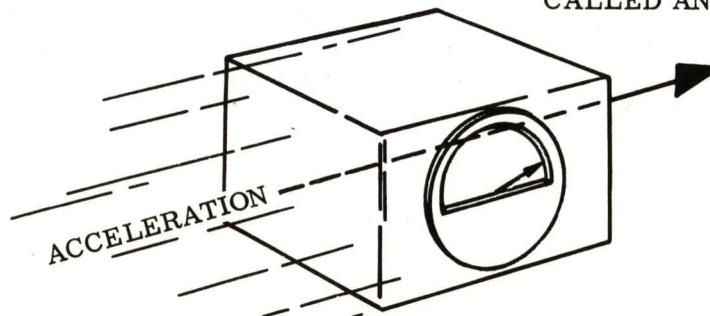
We will mechanize devices which use Newton's second law, $F = MA$, in order to sense:

- A. velocity.
- B. acceleration.
- C. distance.
- D. none of the above.

(12)

(13)

THE DEVICE WE SHALL USE TO SENSE ACCELERATION IS LOGICALLY CALLED AN ACCELEROMETER.



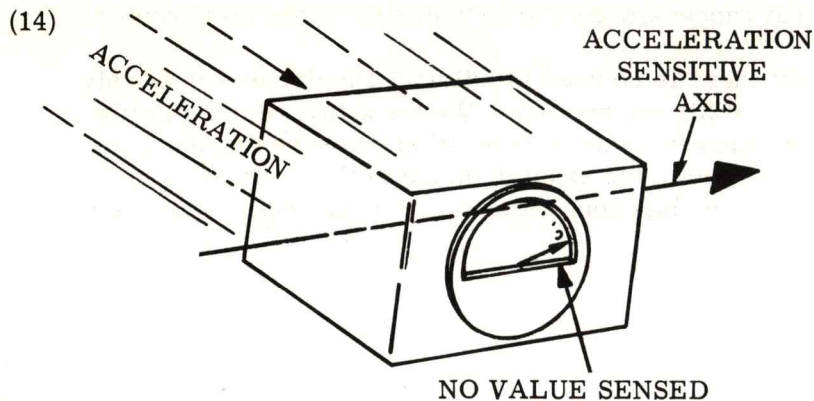
TURN SELECTOR TO POSITION 4

- (14) The accelerometer is a very sensitive instrument that detects acceleration along one axis only. For example, the accelerometer shown in the illustration senses acceleration only along the axis shown. An acceleration in any other direction will not effect this unit.

-
- (15) We now have the basics required for a guidance/navigation problem and solution, namely:
- a. Exact location of start point.
 - b. Exact location of destination.
 - c. A device which mechanizes Newton's second law providing a measurement of acceleration (accelerometer).

-
- (16) If we wish to go from one point to another, and these positions are known exactly, then we know the best route, approximate time enroute at a given speed, the distance between the points and the direction of travel. If we mount our accelerometer to our vehicle, then we will be able to read the acceleration that the vehicle is undergoing at any given time. From this acceleration information we can derive velocity and distance.

-
- (17) Let's start on the trip. Assume we are using a car with the accelerometer mounted on the hood. The sensitive input axis of the accelerometer is pointing forward. When we step on the gas pedal, the car lunges forward (see illustration), the accelerometer senses the acceleration and indicates it. From this acceleration measurement we calculate velocity and, subsequently, distance traveled. From our very gross look at what we are capable of finding out from the accelerometer, it sounds like everything is taken care of as far as measurements are concerned.



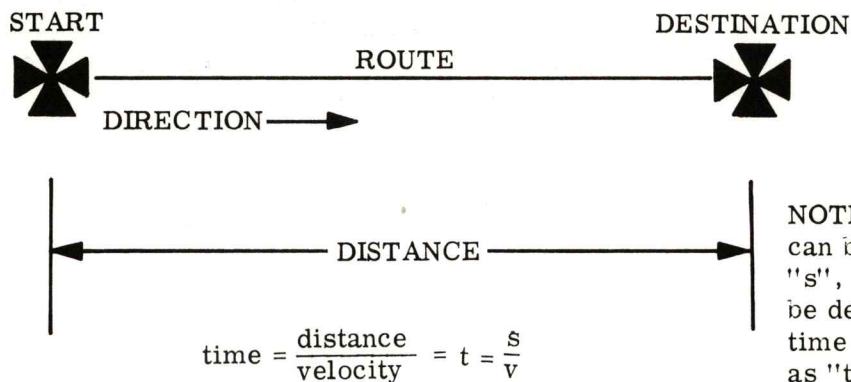
The device called an accelerometer is going to be used to sense acceleration along:

- A. one axis.
- B. two axes.
- C. three axes.
- D. none of the above.

(15)

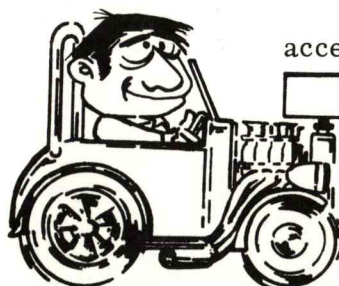
NOTICE. No where do we mention or need any communication with a command center. This is the prime advantage of an inertial guidance/navigation system.

(16)



NOTE: Distance can be denoted as "s", velocity can be denoted as "v", time can be denoted as "t".

(17)



$$\text{acceleration} = \frac{\text{change velocity}}{\text{change in time}} = \frac{\text{change in distance}}{\text{change in time} \times \text{change in time}}$$

Once we sense acceleration, we have the means to resolve values for velocity and distance.

TURN SELECTOR TO POSITION 5

- (18) There is one major problem. What happens if the car deviates from the ideal route?

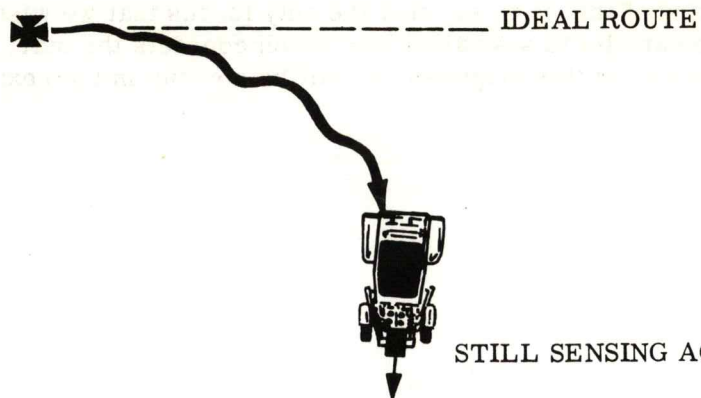
To prove a point, let's assume that there is no road to follow. The driver has to rely on the accelerometer outputs for all of his information. We know that he can readily determine velocity and distance traveled from the acceleration measured by the accelerometer. Further, he already knows the exact distance to the destination so when his accelerometer data tells him he has gone the distance required he should be there -- but he may not be!

-
- (19) The accelerometer senses forward and backward accelerations only; thus if the car changes direction there would be no obvious means of detecting it. In fact, the car could accumulate the required distance traveling in a circle and end up just where it started.

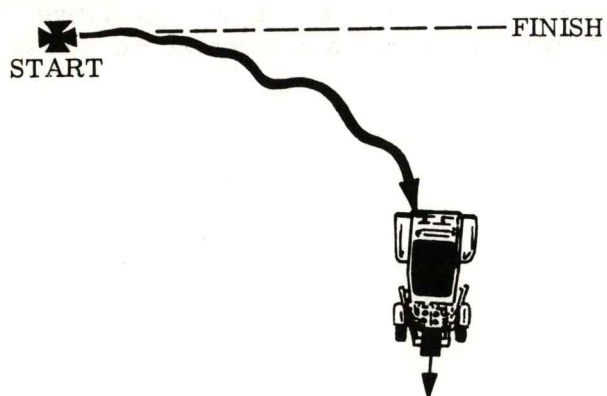
-
- (20) The point that must be made is, "as long as the wheels of the car are turning there is a 'forward' velocity." In order to have reached this velocity, there must have been an acceleration. As far as the accelerometer is concerned - it detects forward acceleration of the car regardless of the direction in which the car is headed.

-
- (21) This example has pointed to a need for some method of isolating the directional movement of the car from the accelerometer so that as the car changes direction the accelerometer will still point in the same direction it did at the start point. In this way, the accelerometer will always sense the acceleration that is in the direction of the destination.

(18)



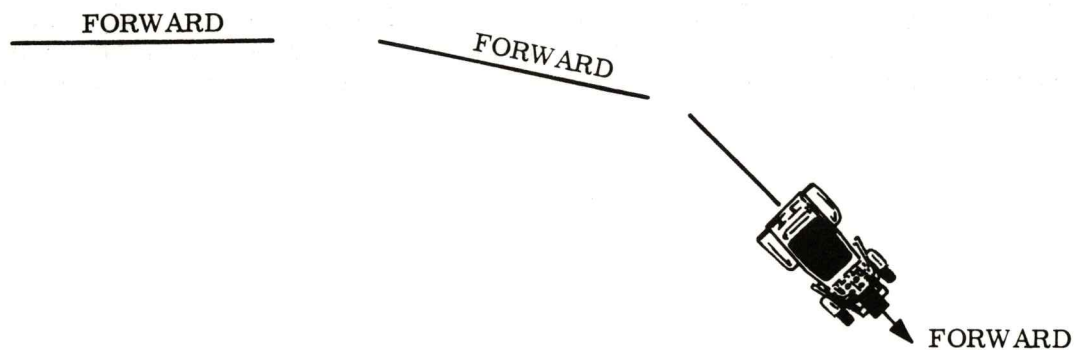
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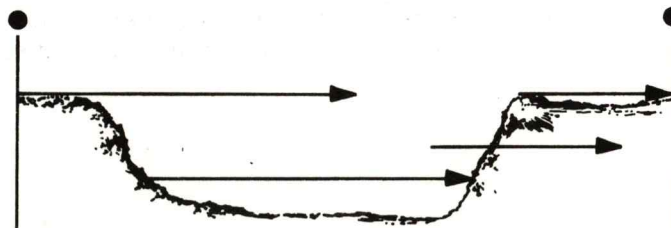
It appears that we must develop some technique of determining _____ as well as sensing acceleration.

- A. acceleration
- B. velocity
- C. direction
- D. none of the above

(20)



(21) So. we mount the accelerometer in a special way which insures that accelerations in the proper direction are sensed.



TURN SELECTOR TO POSITION 6

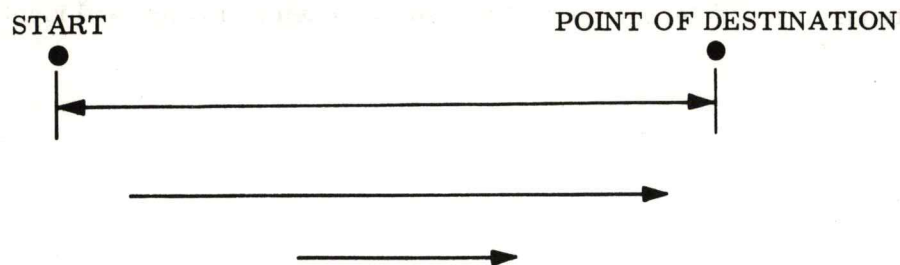
- (22) Another way of thinking of this is to say that the only forces that we wish to measure are those forces that are parallel to a straight line which connects the start point to the destination. The reason for this requirement will be obvious in the next few frames.

-
- (23) The arrow that we have drawn on our black box accelerometer is representative of what we call the positive input axis. It represents the direction in which we can measure a force on a given mass (acceleration).

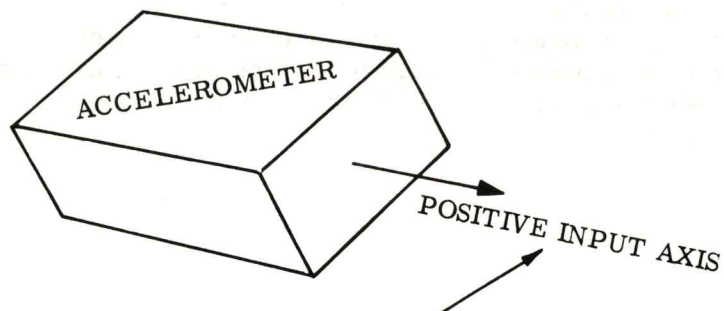
-
- (24) We have already implied that obtaining a measurement of acceleration without knowing its direction would result in velocity and distance calculations that are quite meaningless. In order for us to provide both acceleration and direction, it is imperative for us to know the direction that the positive input axis of the accelerometer is pointed at all times.

-
- (25) Having the positive input axis of the accelerometer pointed in one direction - never changing - will allow us to interpret acceleration as a directional quantity. In our example of the auto driving from one point to the other, the accelerometer that we point at the destination prior to leaving will always point in the same direction regardless of vehicle motion (it is well to recognize that the accelerometer positive input axis is not pointing to the destination at all times but is pointing in a direction parallel to its original orientation).

(22)

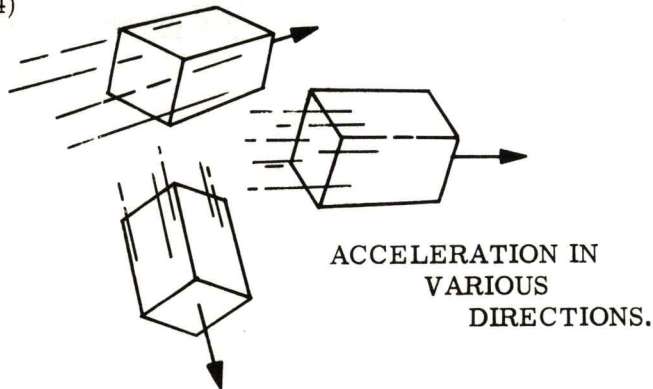


(23)



This must become common terminology in your study of inertial devices.

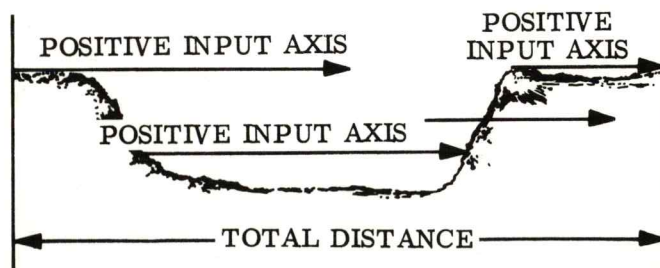
(24)



Inherent in obtaining an accurate knowledge of velocity and distance will be the capability to sense acceleration with a known _____.

- A. direction
- B. velocity
- C. acceleration
- D. distance

(25)



TURN SELECTOR TO POSITION 7

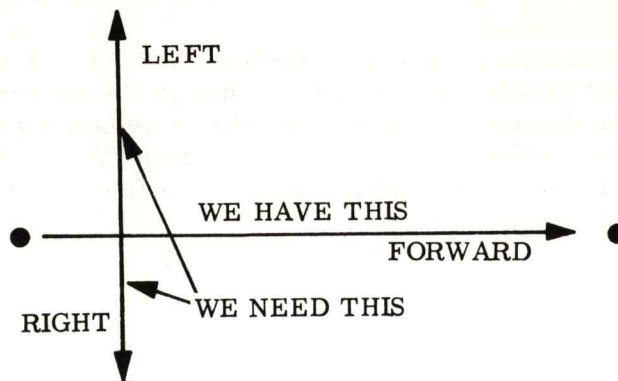
- (26) There seems to be one more unfulfilled need other than developing a method of keeping the positive input axis of the accelerometer pointed in one direction. Doesn't it sound reasonable that in order for us to proceed from one point to another we had better incorporate another accelerometer that measures acceleration left and right?

-
- (27) The purpose of this inertial guidance/navigation system was to allow us to go from one point to another. If we are not concerned at this time about altitude, then we can determine the exact position on a plane surface with two directional distances. To provide the second distance, we will introduce a second accelerometer which has its positive input axis perpendicular to the first.

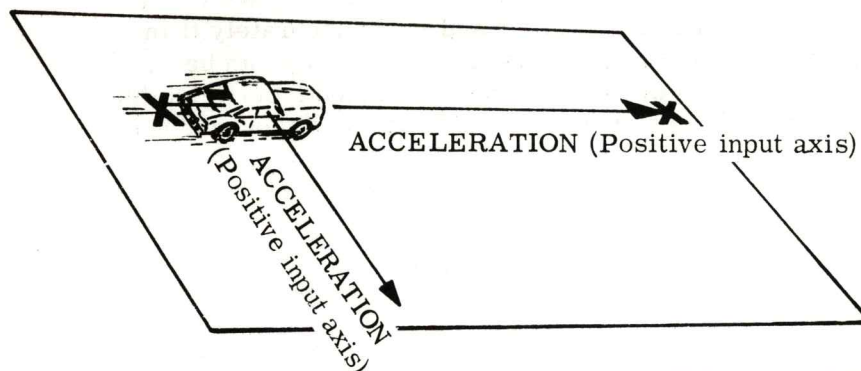
-
- (28) Let's call the accelerometer, that we placed on the car first, the "Forward Accelerometer" and the one that has its positive input axis pointing 90° from this the "Side Accelerometer".

-
- (29) Now if we wish to proceed from one point to another we can describe the destination location by distance forward and distance side as determined by our accelerometers. No outside information is required.

(26)



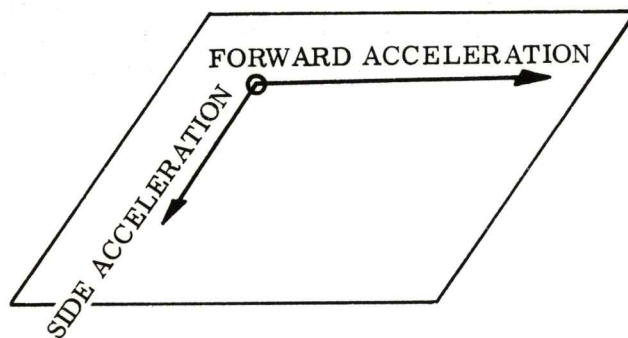
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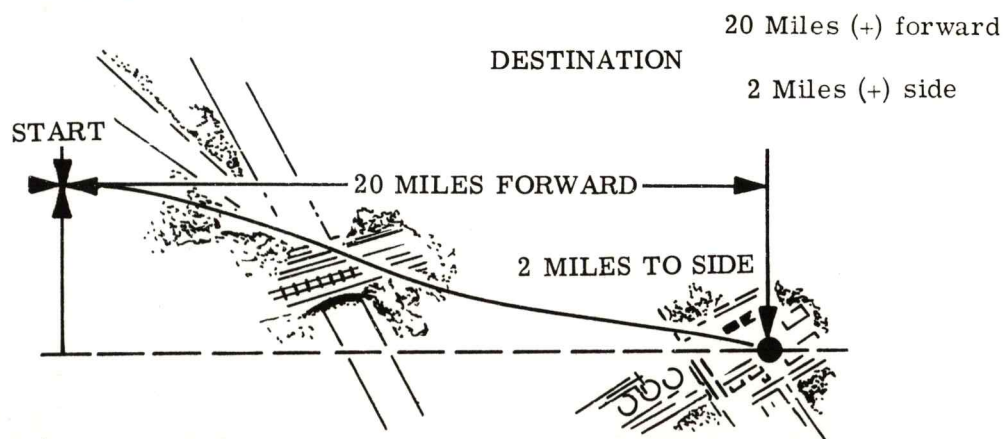
Position in a plane is determined by:

- A. two directional distances.
- B. one directional distance.
- C. an angle and a plane.
- D. a vertical accelerometer.

(28)



(29)



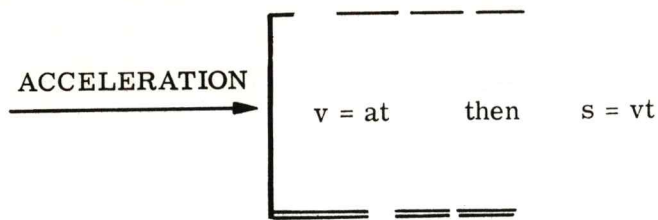
TURN SELECTOR TO POSITION 8

- (30) It should be reviewed that if, according to Newton's laws, we have a method of mechanizing the equation $F = MA$ and if "A" (acceleration) is due to, in our case, vehicle motion; then multiplying "A" by the duration of acceleration (time) we obtain velocity "V" and by multiplying velocity (V) by the duration (time) of a given "V" we obtain distance. A given distance in the forward and sideward direction define our position. This concept is of paramount importance.

-
- (31) In order for us to perform the mathematics required to obtain velocity and distance information, along with keeping track of time, we will need a computer. We use a computer because it can do the mathematics much faster and more accurately than a human could ever hope to. As you saw in the previous frame, velocity can be determined once we know acceleration, and distance can be calculated from velocity. The computer of a guidance system might perform these calculations a thousand times per second always keeping an up to date accurate value.

-
- (32) We now have two accelerometers, a computer and some knowledge on the use of these components in an inertial guidance/navigation system. We must now go back and see how we can stabilize the accelerometers so that they do not change their input axis orientation regardless of vehicle motion. The system used to stabilize the accelerometers will logically be called the "stabilization system".

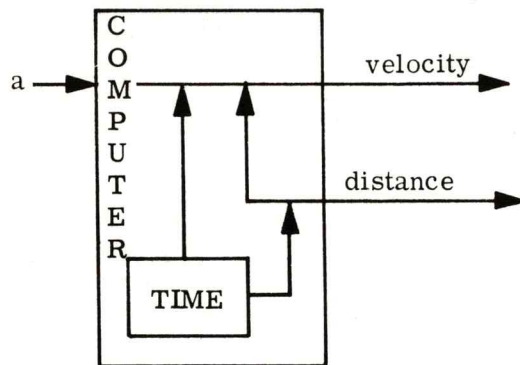
(30)



Once acceleration is sensed by the mechanization of our guidance system, it will be possible to determine:

- A. velocity
- B. distance
- C. neither A or B is correct.
- D. both A and B are correct.

(31)



The calculation of velocity and distance is usually performed by a:

- A. servo.
- B. amplifier.
- C. computer.
- D. all of the above are correct.

(32)

WE MUST DEVELOP A STABILIZATION SYSTEM!

TURN SELECTOR TO POSITION 9

(33) Prior to viewing the theory involved in developing a stabilization system, we shall quickly recap those major items which you must remember to fully understand inertial guidance and navigation.

1. We first saw that Newton's three laws pertaining to motion were to be directly applicable to the theory of inertial guidance and navigation.

Law of inertia

Law of $F = MA$

Law of action equals reaction

2. An inertial guidance/navigation system is mechanized to sense acceleration, and to calculate velocity and distance from this sensed input.
3. Inertial guidance/navigation is self-contained within the vehicle of which it is a part. No external commands or signals are required as it functions to solve navigation and guidance problems.
4. The problem we are faced with in navigation is to determine our position at any point on land, in the air, sea or space.
5. The problem we face in a guidance/navigation system is to determine where we are on land, in the air, sea or space, knowing specifically where we started from. Also we must know specifically where (what point) we are going and initiate any vehicle correction signals needed to guide our vehicle to this desired destination.
6. The device used in mechanizing Newton's second law ($F = MA$) is called an accelerometer. As we have learned, an accelerometer is sensitive along one axis. This axis is commonly called a "positive input axis".
7. In order to derive intelligible values of velocity and distance from our accelerometer, we must insure that it maintains the direction that it had initially. To see how this will be accomplished, we shall view a stabilization system next.


(33)

NEWTON'S LAWS:
"INERTIA"
"F = MA"
"ACTION = REACTION"

INERTIAL GUIDANCE/NAVIGATION
SYSTEMS ARE SELF CONTAINED.

A device which senses acceleration is
called an "ACCELEROMETER".

ONCE ACCELERATION IS
SENSED, THE SYSTEM CAN
DERIVE VELOCITY AND DISTANCE.



COMPUTERS ARE USED TO PERFORM
THIS CALCULATION.

Newton's second law states that:

- A. force equals mass times acceleration.
- B. action equals reaction.
- C. a body in motion tends to stay in motion.
- D. none of the above.

The axis along which an accelerometer is sensitive to acceleration is usually called the:

- A. all of these answers are correct.
- B. acceleration axis.
- C. output axis.
- D. positive input axis.

From values of acceleration, the guidance/navigation system computer will calculate:

- A. velocity.
- B. velocity and distance.
- C. distance.
- D. none of the above.

The system which will maintain the accelerometers in known directions is referred to as the:

- A. stabilization system.
- B. computer system.
- C. accelerometer system.
- D. navigation system.

(34) BASIC GYROSCOPE THEORY

We have established a need for a stabilization system. (Vehicle motion must not displace our accelerometer positive input axes.) Our stabilization system will make use of devices called gyros. If you are already familiar with gyro operation proceed to frame 55. If not, proceed to the next frame.

-
- (35) Given: A mass spinning about an axis. If this axis is displaced in a rotational manner a reaction will take place that is unique to spinning masses. The reaction is called "precession" and can be explained by application of Newton's second law of motion. We will not discuss the mathematical analysis of the reaction but rather the physical interpretation of what happens. (A complete discussion of precession is presented in a later volume of this series.)

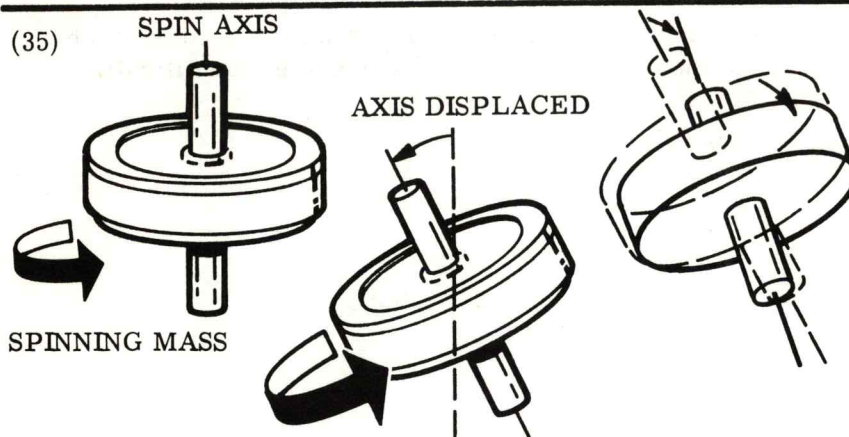
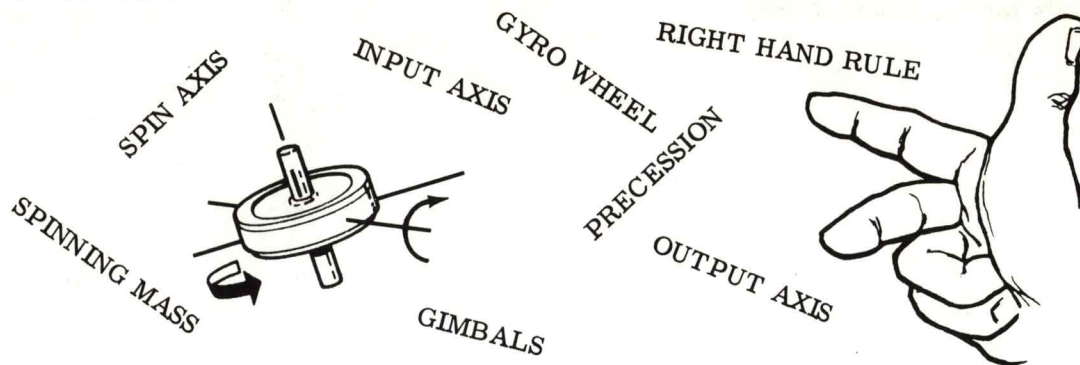
-
- (36) In a gyro, the spinning mass is a wheel. A closer look at the wheel will reveal three axes two of which are invisible, but definable, and a third which is readily visible. The three are:

1. SA - the spin axis (visible - the mass spins about this axis)
2. IA - the input axis (invisible - an axis located at 90° to the spin axis)
3. OA - the output axis (invisible - an axis mutually perpendicular to the other two axes)

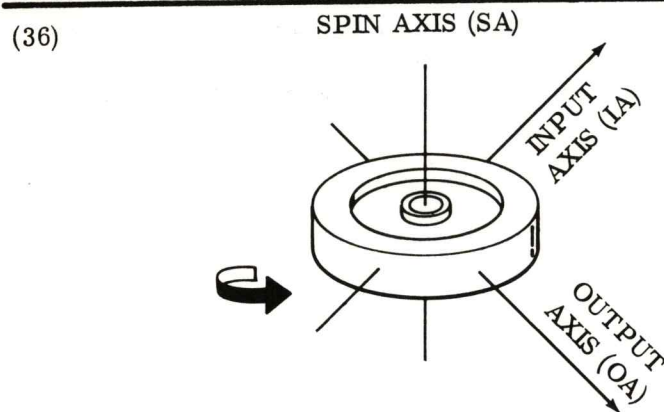
-
- (37) The spin axis is the axis about which the mass is rotating. If an arrow is placed on the end of the axis that is pointing in the direction of the right thumb when the fingers of the right hand point around the axis in the direction of wheel rotation, then this arrow identifies the positive rotational direction. This arrangement of the right hand (fingers curled in the direction of rotation, thumb points to plus end of axis) is commonly referred to as the "right hand rule".

NOTE: This right hand rule is often applied in standard rotational vector notation where the fingers are curled in alignment of a rotational value, and the thumb defines the direction of a positive vector. At present we will be using the right hand rule to determine the positive ends of axes and the direction of arrows which in reality represent vectors. This is explained in much greater detail in a later text.

(34) IF YOU KNOW BASIC GYRO THEORY PROCEED TO FRAME 55.



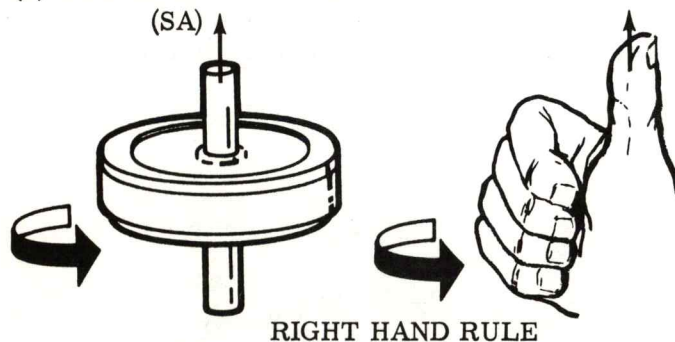
IF WE ATTEMPT TO ROTATIONALLY DISPLACE THE AXIS OF THE SPINNING MASS -- AN ACTION CALLED PRECESSION OCCURS (PRE - CESS - SHUN).



That axis about which the spinning wheel rotates is called the:

- A. all of these answers are correct.
- B. input axis.
- C. output axis.
- D. spin axis.

(37) (+) POSITIVE END OF SPIN AXIS (SA)



In the illustration shown, when using the right hand rule, the fingers are curled in the direction of the rotational input and the thumb points to:

- A. the up direction.
- B. the negative input spin.
- C. the wheel rotation.
- D. the positive end of the spin axis.

TURN SELECTOR TO POSITION 11

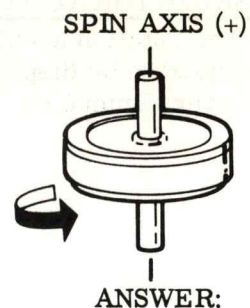
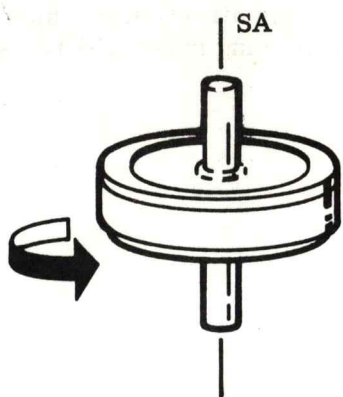
- (38) To insure that you followed the information in frame 37, try to figure out the positive spin axis for the wheel shown.

-
- (39) It is important that you understand the significance of these "arrowheads" because each one of our three axes will be related to the others via these positive axes identification symbols (arrowheads).

-
- (40) With just a spinning wheel in space (no mounting restrictions) we can assume our second axis (input axis) anywhere, as long as it passed through the center of the wheel and is perpendicular to the spin axis. Once the input axis is defined, the output axis will be located 90° from this input axis.

-
- (41) We'll pick one of these axes and discuss its implication and operation. The rule of the right hand will again be applied to identify a positive rotation about the input axis. That is to say, if we try to move the spinning mass about the input axis as shown, the arrow will point as indicated. This rotation is a positive input rotation by definition.

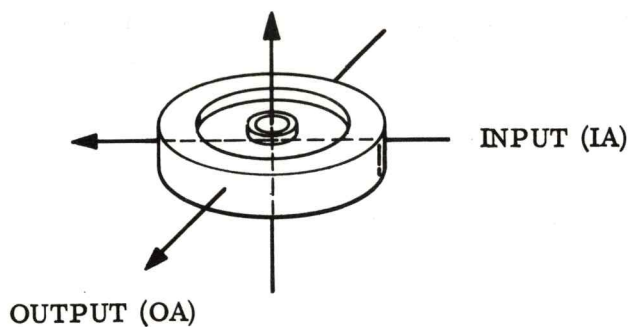
(38)



(39)

AXES

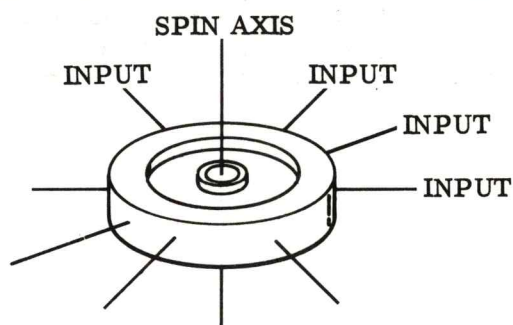
SPIN (SA)



In the diagram shown, it appears that all three axes are:

- A. input axes.
- B. mutually perpendicular.
- C. spin axes.
- D. right triangles.

(40)

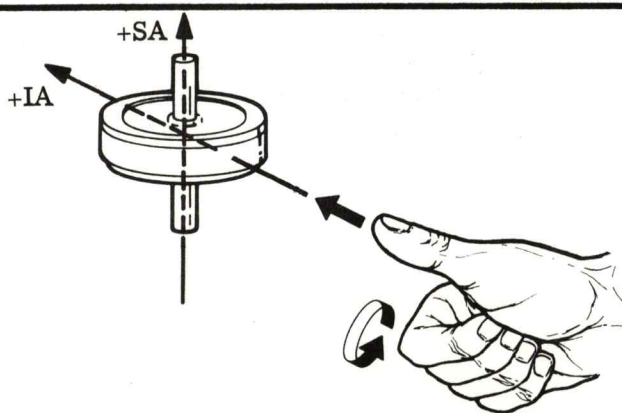


The spin axis is:

- A. parallel to the input axis.
- B. is undefined.
- C. perpendicular to the plane containing the input axis.
- D. parallel to the wheel.

THE INPUT AXIS. . . IT COULD BE ANY OF THE ABOVE.

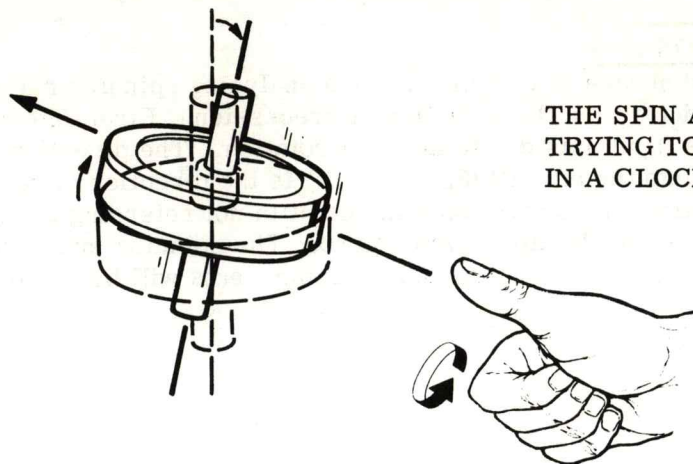
(41)



TURN SELECTOR TO POSITION 1

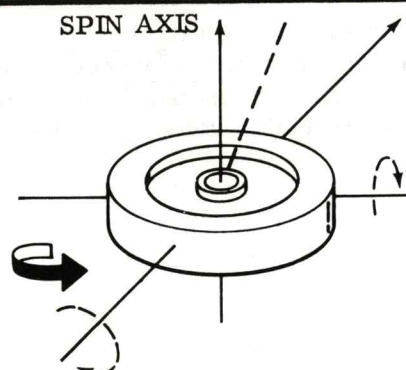
- (42) The rotation about the input axis really defines the direction in which the spin axis is trying to be displaced. We will see that this spinning mass will resist this motion in a very unique way.
-
- (43) If a rotation is developed about the input axis (which tries to displace the spin axis) a resulting rotation about a third axis (output axis) will result. The output axis is an imaginary axis which is perpendicular to both the spin axis and the input axis and passes through the center of the wheel.
-
- (44) The rotation about the output axis, as a result of rotation about the input axis, is called precession and is always displayed when a rotating mass is subjected to an attempted rotation of the spin axis. The direction of precessional rotation (rotation about the output axis) is predictable.
-
- (45) In order to place an arrow on the output axis to define its positive rotation we must consider the positive spin axis and the positive input axis. If you imagine the positive spin axis rotated into the positive input axis and the resulting rotation is signified by the fingers of the right hand, then the thumb of the right hand points to the positive output axis.

(42)



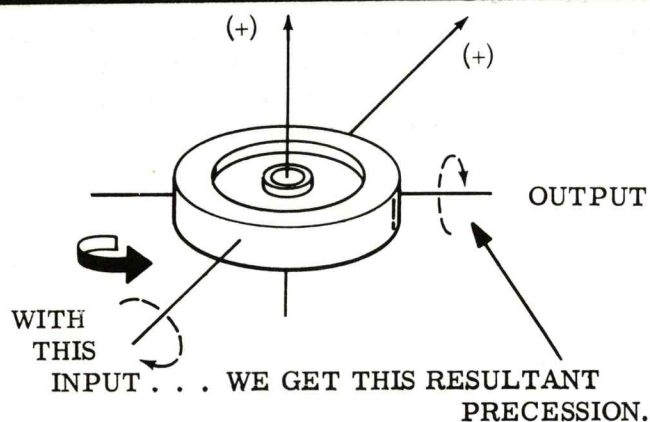
THE SPIN AXIS IS
TRYING TO BE DISPLACED
IN A CLOCKWISE DIRECTION

(43)



AS THIS INPUT. . . . TRIES TO DISPLACE THE GYRO. . . . IT REACTS ABOUT
THE OUTPUT AXIS AS SHOWN.

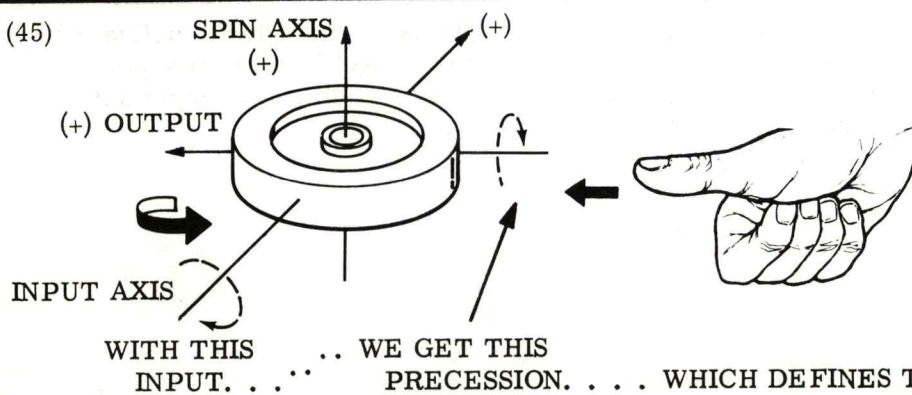
(44)



When a rotation is caused about
the input axis, the resulting
rotation about the output axis is
called:

- A. input rotation.
- B. spin axis movement.
- C. precession.
- D. spin.

(45)



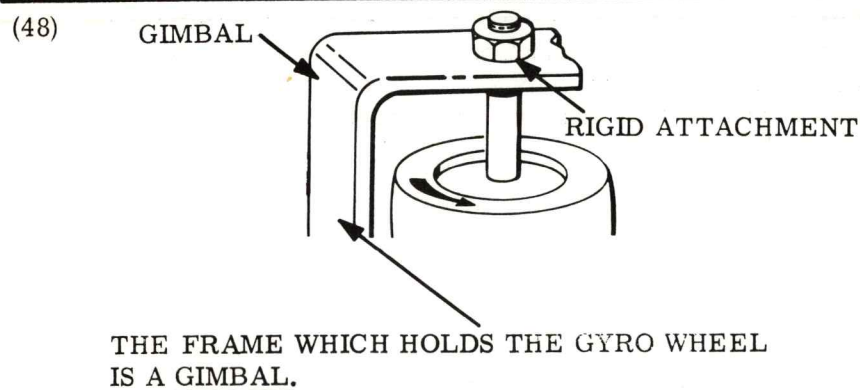
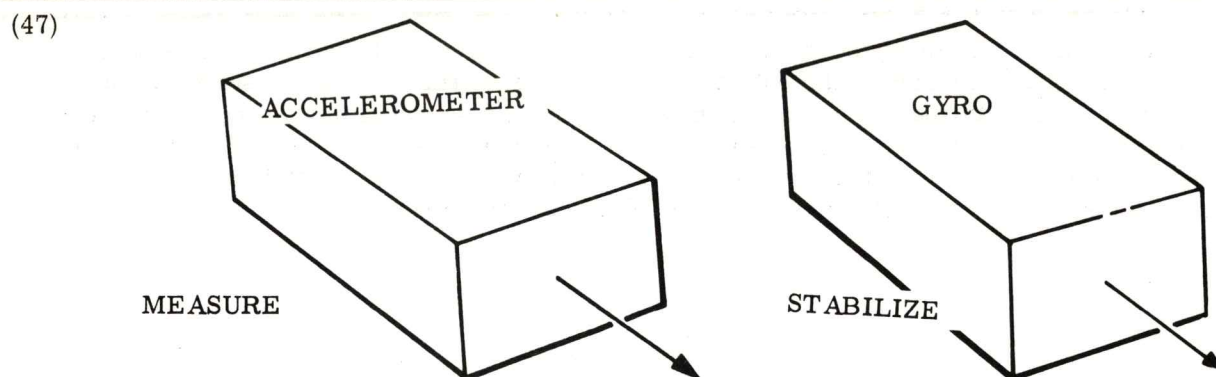
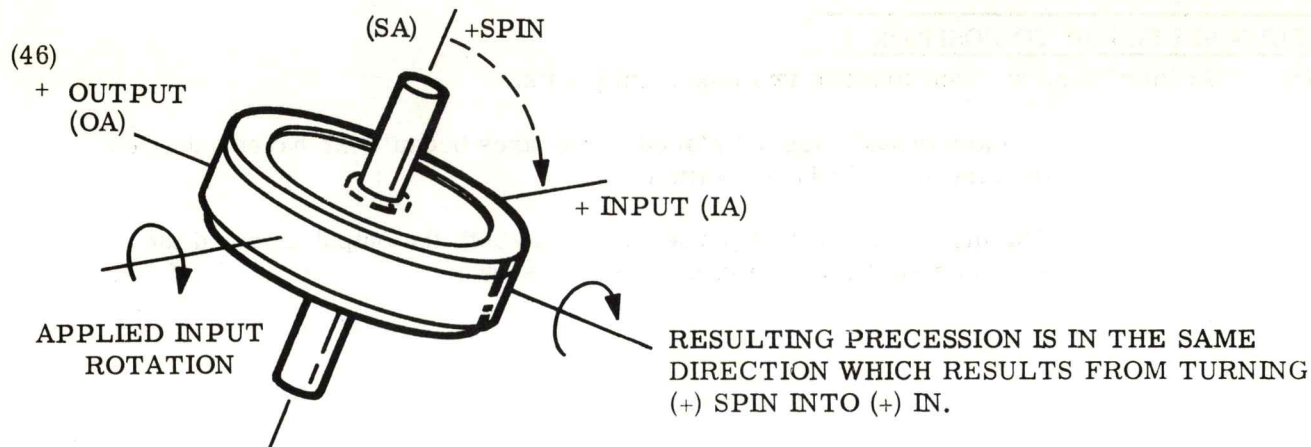
TURN SELECTOR TO POSITION 2

- (46) "Spin into IN" is a good phrase to remember when analyzing spinning masses. By this we mean that it's easy to determine the direction of precession. First determine the positive spin axis, then the plus input axis due to an input rotation. The direction you would have to rotate the plus spin into the plus IN (Spin into IN) is the direction of resulting precessional rotation. See the illustration. There isn't any point in not referring to the spinning mass as a gyro, so from now on we'll call a gyro a gyro. The spinning mass will become our gyro wheel. (A detailed look at the gyro and its components will be found in a later volume of this series.)

-
- (47) Keep in mind that we are in the process of building a stabilization element for our guidance system. Its sole purpose is to provide a stable reference from which our accelerometers can measure. The development of gyros and the associated stabilization loop is not for measuring acceleration or for providing velocity or distance information.

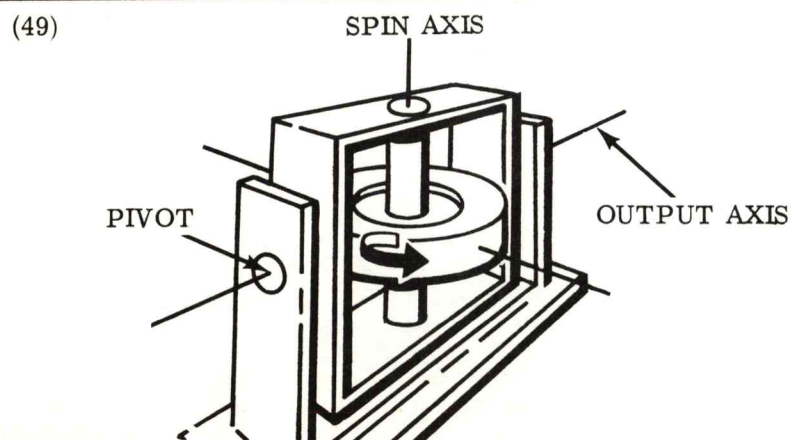
-
- (48) In order for our gyro wheel to be functional we must place it in a realistic environment. (So far we have only considered a wheel spinning in space.) Let's mount the wheel in a frame which we'll call a gimbal. For practical purposes we'll assume that the gyro wheel can be rotated by a motor which is located inside the wheel

-
- (49) With the wheel mounted in the gimbal we can define the spin axis. In order to define the input and output axes of the gyro we must add more hardware. We'll add a pivot point for the gimbal as shown in the illustration. This pivot point will define the output axis of the gyro. Can you show where the input axis must be?



The terminology used to describe the frame which holds the gyro wheel is:

- A. gimbal.
- B. wheel holder.
- C. frame.
- D. none of the above.



The input axis of the gyro shown in the illustration is:

- A. all of these answers are correct.
- B. aligned with the output axis.
- C. perpendicular to the spin axis.
- D. mutually perpendicular to the spin axis and output axis.

TURN SELECTOR TO POSITION 3

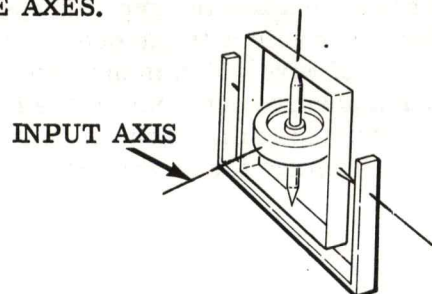
(50) In this frame we want to make two important points.

1. The arrowheads are not placed on the axes because we haven't defined the direction of wheel rotation.
2. The input axis must be perpendicular to both the output axis and the spin axis so it must be in the position shown.

(51) If a rotation is felt about the gyro input axis, then the gyro will precess, causing a proportional rotation about the output axis. In other words, by the construction of our gyro, any rotation felt about the input axis will cause the gimbal to rotate because the gyro wheel is forcing it to do so. This is just like we saw before except that now our gyro is supported by the gimbal. We already know that the direction of input rotation will determine the direction of output rotation (SPIN into IN).

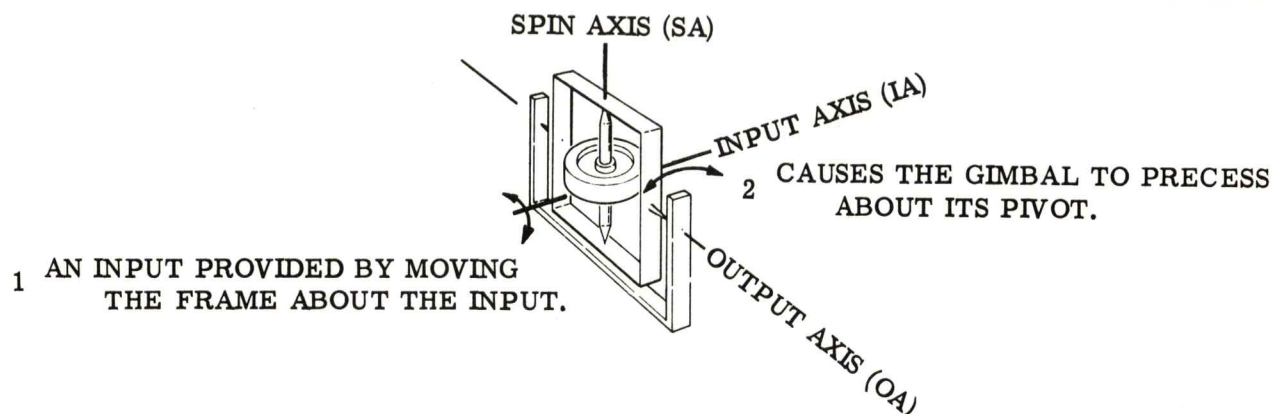
(52) Now what can we do with this gyro to make it a functional stabilizing device for our accelerometers? Obviously we need additional hardware. Let's continue to develop the stabilization system and add the needed hardware as we need it.

- (50) AS WE HAVEN'T SEEN ROTATIONS YET. . . . WE CAN'T USE THE RIGHT HAND RULE TO DEFINE POSITIVE AXES.

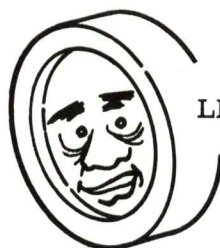


THE INPUT AXIS IS MUTUALLY PERPENDICULAR TO BOTH THE SPIN AND OUTPUT AXES.

(51)



(52)



LET ME STATE MY PRECESSION.

TURN SELECTOR TO POSITION 4

- (53) Since we know the reaction that the gyro will undergo when a rotation is provided about its input axis, it seems only right that we allow the gyro to "speak". Put a pointer on the output axis shaft. This pointer will rotate with the output axis as the gyro precesses. Allow the pointer to ride on a coil of wire which is mounted on the gyro holder. If this coil of wire (potentiometer) has a positive potential on one end and a negative potential on the other end and a grounded center tap (null), then as the gyro precesses the gyro could "talk" by indicating a + or - voltage for direction and a voltage amplitude for amount of rotation.

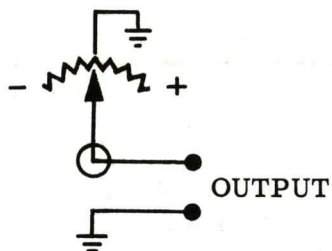
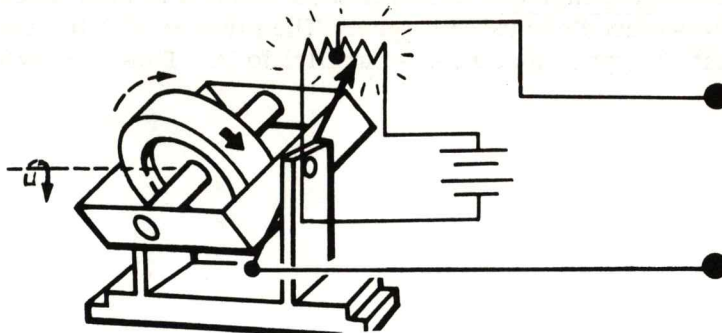
-
- (54) A positive rotation about the input axis causes a positive rotation about the output axis causing a positive voltage to appear at the output of the potentiometer. An opposite rotation (negative direction) about the input axis results in a negative voltage output. In either case, the magnitude of the voltage is dependent upon the magnitude of the input rotation. This is true because depending upon how much of an input is sensed, the gyro precesses a proportional amount.

(55) THE STABLE MEMBER

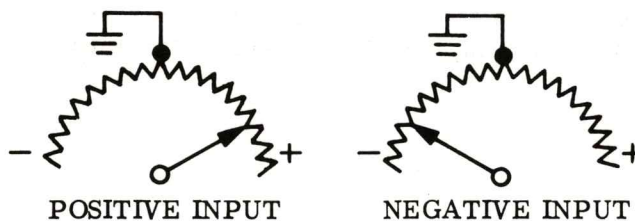
Now that we have given the gyro the opportunity to "speak" via the potentiometer, let's provide a use for the output. Let's place the gyro on some sort of mount, we will call this mount the stable member. (Later you will see that the fruits of the gyro effort will be to provide a stable mounting for our accelerometer.)

(53)

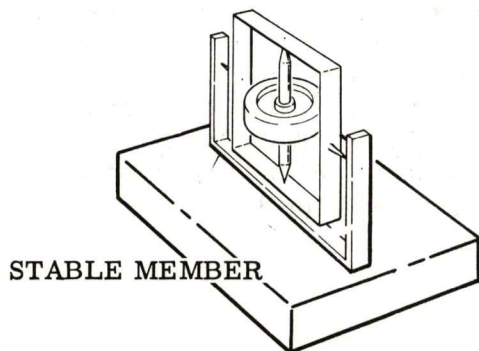
SPIN AXIS



(54)



(55)



The purpose of the potentiometer on the pivot at the output axis of the gyro is to:

- A. generate a signal when the gyro precesses.
- B. indicate magnitude and direction of precession.
- C. all of these answers are correct.
- D. indicate when a rotation is felt about the gyro input axis.

TURN SELECTOR TO POSITION 5

- (56) The stable member is now placed inside a gimbal much larger than, but similar to, the one we used around our gyro. The pivot axis of the stable member gimbal is placed so that the gyro input axis is parallel to it. This is very important as you will see.

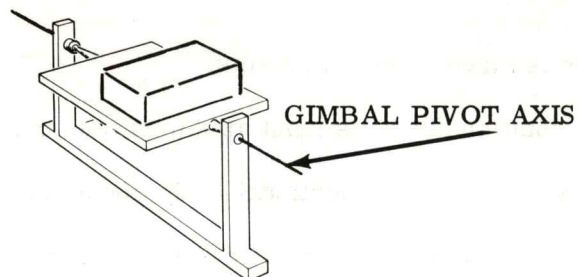
-
- (57) All we need now are two more things, and we will be pretty well finished with one stabilization loop. We need:

1. A DC torque motor. (We need a motor with a lot of starting strength because it will have to make many rapid starts and stops.) Also it must be able to be made to run in both the forward and reverse direction which is determined by the polarity of the input.
2. Some wire.

-
- (58) The motor will be placed on one end of the gimbal pivot axis. (It doesn't make any difference which end.) The rotor of the motor is attached to the gimbal. When the motor is turned on, the stable member turns with respect to the gimbal.

-
- (59) Now that we have all the equipment in place, let's wire the circuit and analyze its operation. From the pointer of the potentiometer we will run a wire to the torque motor. The other wire is attached to the center tap of the potentiometer. When the pointer is off the center point it will introduce either a positive or negative voltage to the motor. The polarity of the motor input determines the direction of rotation of the stable member with respect to the gimbal. When the pointer is pointed at the center tap, a null condition exists and the motor does not run.

(56)

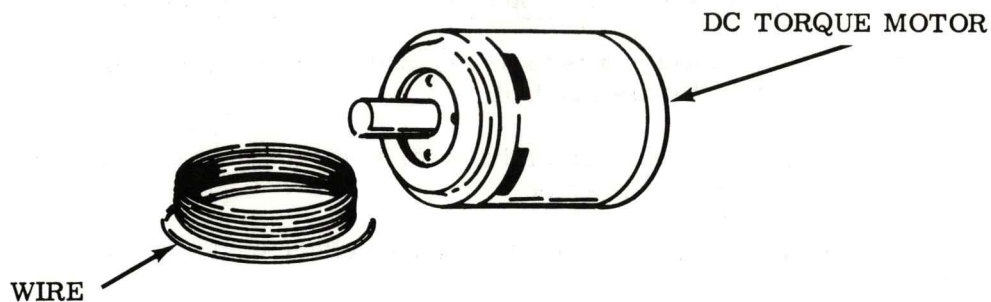


Now we see that the stable member, with a gyro on it, will be supported in a frame called a:

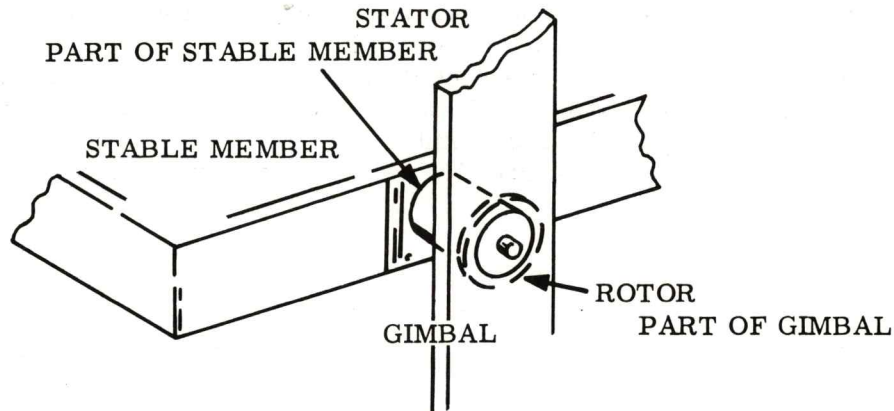
- A. gimbal.
- B. gimbal.
- C. gimbal.
- D. gimbal.

*Easy question, huh?

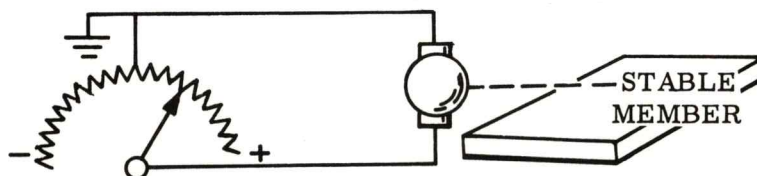
(57)



(58)



(59) REMEMBER!.THIS POTENTIOMETER WAS ON THE GYRO'S OUTPUT AXIS. WHEN IT MOVES THE GYRO HAS BEEN ROTATED ABOUT ITS INPUT AXIS.



TURN SELECTOR TO POSITION 6

(60) In operation this is what happens:

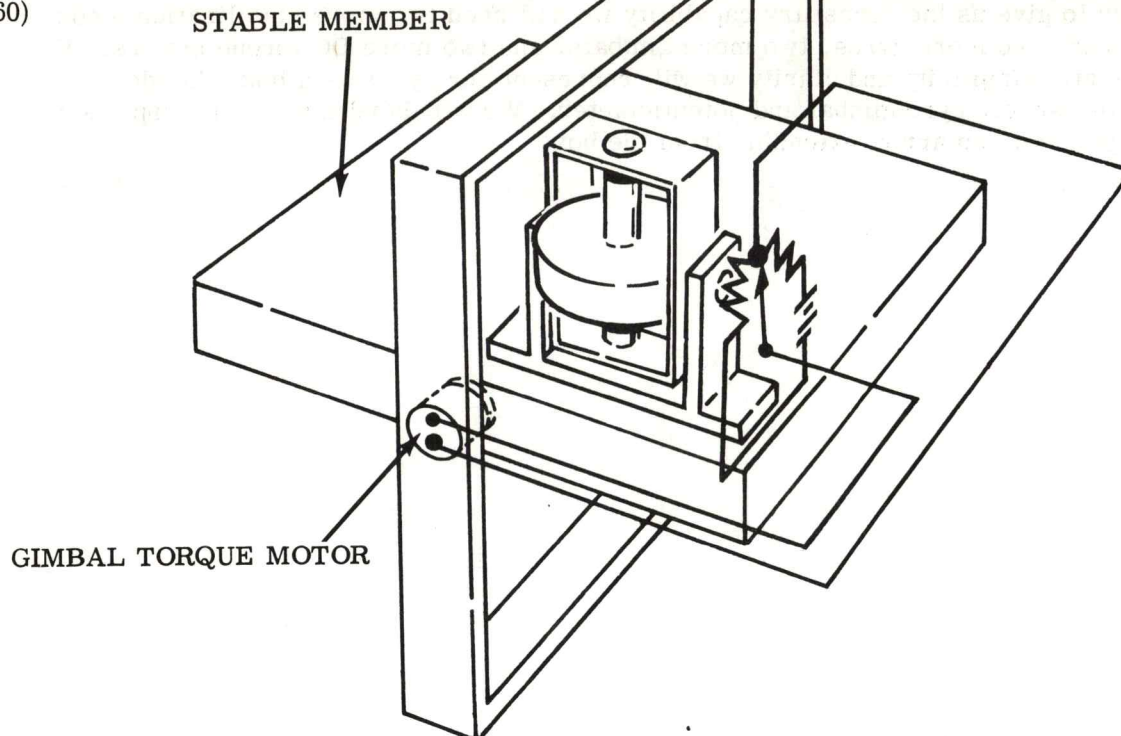
1. The stable member is moved about its pivots.
2. The gyro senses a rotation about its input axis (positive or negative).
3. The gyro precesses an amount proportional to the input rotation.
4. Due to precession, the output axis is rotated a proportional amount.
5. The pointer deflects a proportional amount and in a direction which indicates the inputs direction.
6. The gimbal DC torque motor operates causing the stable member to rotate in a direction opposite the original movement.
7. The platform moves to its original position and causes the gyro to sense an input opposite than the original.
8. The gyro precesses in the opposite direction causing the pointer to return to null (center position).
9. When the pointer is centered, the voltage output is zero and the motor stops

Read this frame approximately 3000 times or less! (It is imperative that you see the concept.)

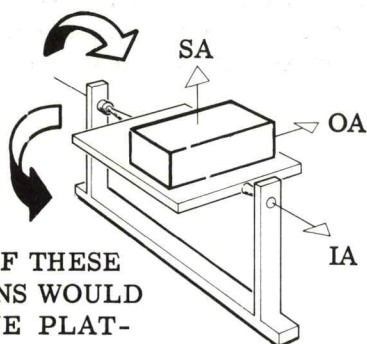
- (61) Our single gyro stabilization loop works very well for rotations which have a component about the gyro input axis. If a rotation is applied to the platform which does not have a component about the gyros input axis. . . . nothing will happen. For example: If one were to rotate the stable member about an axis which is 90° from the gimbal pivot axis - none of this would be felt by the gyro and no corrective action could or would take place.

-
- (62) It probably is becoming more obvious that in order to completely isolate the stable member from vehicle motion we need more stabilization loops like the one just built. (Our goal is to have the capability of sensing, and correcting, any rotational movement of the stable member about any axis.) We must do this if we are planning to mount the accelerometers on a stabilized reference.

(60)



(61)



EITHER ONE OF THESE TWO ROTATIONS WOULD NOT CAUSE THE PLATFORM TO ROTATE ABOUT THE GYRO IA.

In order for our gyro to precess it must sense an input rotation about:

- A. its input axis.
- B. its output axis.
- C. the spin axis.
- D. none of the above.

(62)

RIGHT NOW WE HAVE CONSTRUCTED A GIMBALED STABLE MEMBER WHICH IS MADE STABLE ABOUT ONE AXIS ONLY. IN STABILIZING THIS MEMBER OR PLATFORM IN THREE DIMENSION, WE WILL HAVE TO ADD ADDITIONAL GIMBALS, LOOPS AND GYROS.

TURN SELECTOR TO POSITION 7

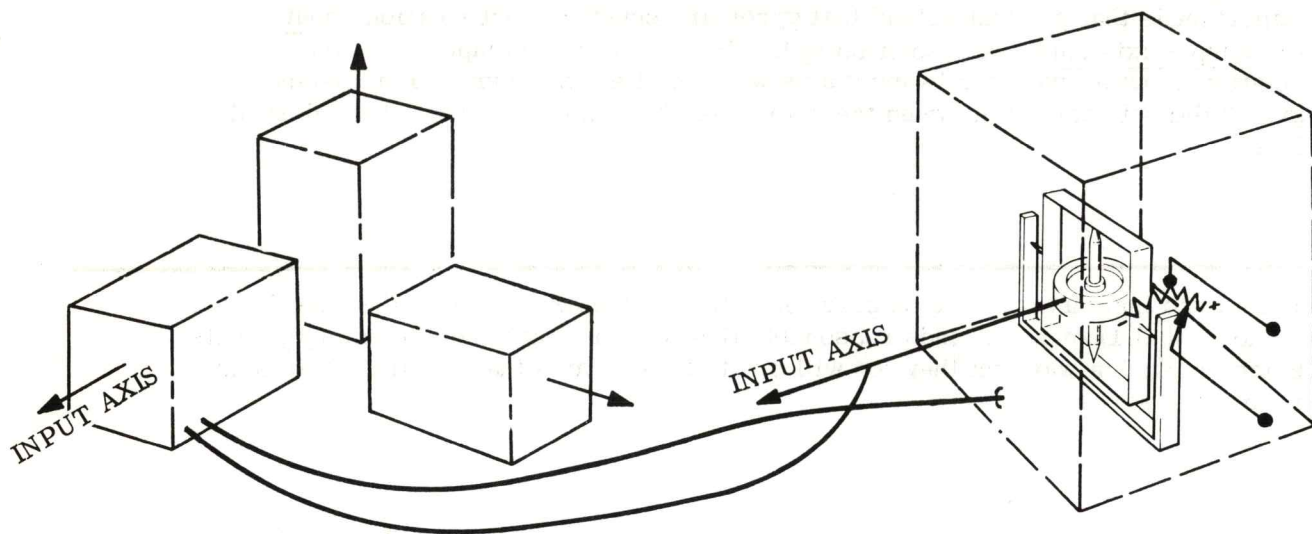
- (63) In order to give us the necessary capability we will need two more stabilization loops. This means two more gyros, two more gimbals, and two more DC torque motors. For diagramatic simplicity and clarity we will represent our gyros as a box. Inside the box is the wheel, gyro gimbal and potentiometer. We will label the positive input axis of the gyro with an arrow extending from the box.

-
- (64) Now let's add one stabilization loop at a time until we have the desired stable member. We already have one gyro mounted on the stable member and we have the associated stable member gimbal. We will label this equipment as "Gyro 1" and "Gimbal Axis 1" or in general "Stabilization Loop 1".

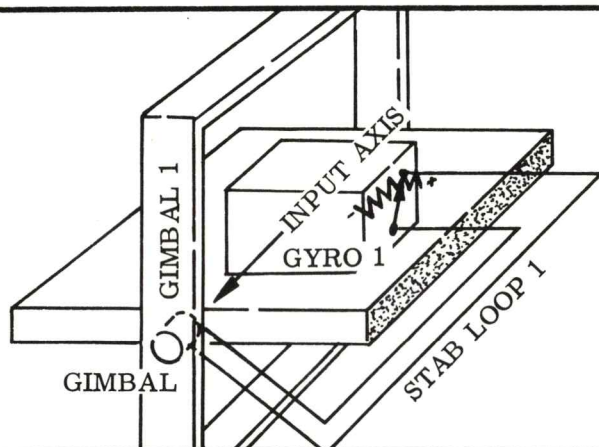
-
- (65) The addition of stabilization loops 2 and 3 will require us to know what orthogonality implies.

To be orthogonal is to be mutually perpendicular. The axis system shown in the illustration is an orthogonal system.

- (63) ON THE STABLE MEMBER WE WILL MOUNT THE GYROS AS BOXES WITH ONLY THEIR POSITIVE INPUT AXIS EXTENDING AS AN ARROW.



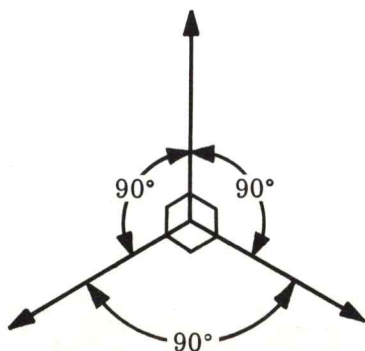
(64)



We have designed our system such that the output of a gyro is applied to a DC torque motor which repositions:

- A. the potentiometer directly.
- B. the computer.
- C. the stable member.
- D. none of the above.

- (65) ALL THREE AXES ARE MUTUALLY PERPENDICULAR.



By placing three gyro input axes in an orthogonal arrangement we can say that these axes are _____ with respect to one another.

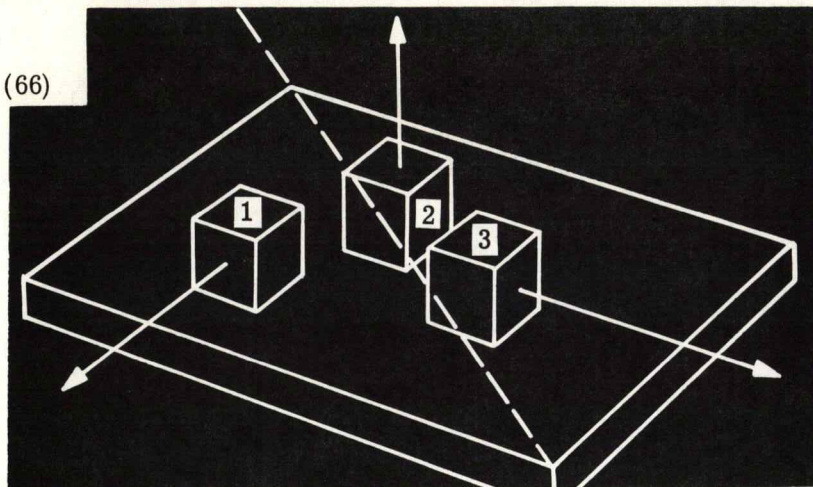
- A. 45°
- B. 180°
- C. 270°
- D. 90°

TURN SELECTOR TO POSITION 8

- (66) If gyros 1, 2 and 3 are mounted on the stable member so that their input axes are orthogonal, then any rotational movement of the stable member will be sensed by one gyro or a combination of gyros. As an example, gyros 1 and 3 would sense the rotation about the imaginary dashed axis. Neither would sense the full rotation. In fact, both would feel .707 of the total. The number is not important; what is important is that you understand that gyros are sensitive to a rotation about their input axis only. Any rotation which does not have a component of the rotation about a given gyro's input axis will not effect that gyro. For instance, gyro 2 did not feel a thing when the stable member was rotated about the dashed line.

-
- (67) If the gyro input axes are to be parallel to the gimbal axes (as was the case for gyro 1 and gimbal 1) then it sounds reasonable that we must have the remaining gimbals placed in such a way that they too will pivot about an axis that is parallel to their respective gyros.

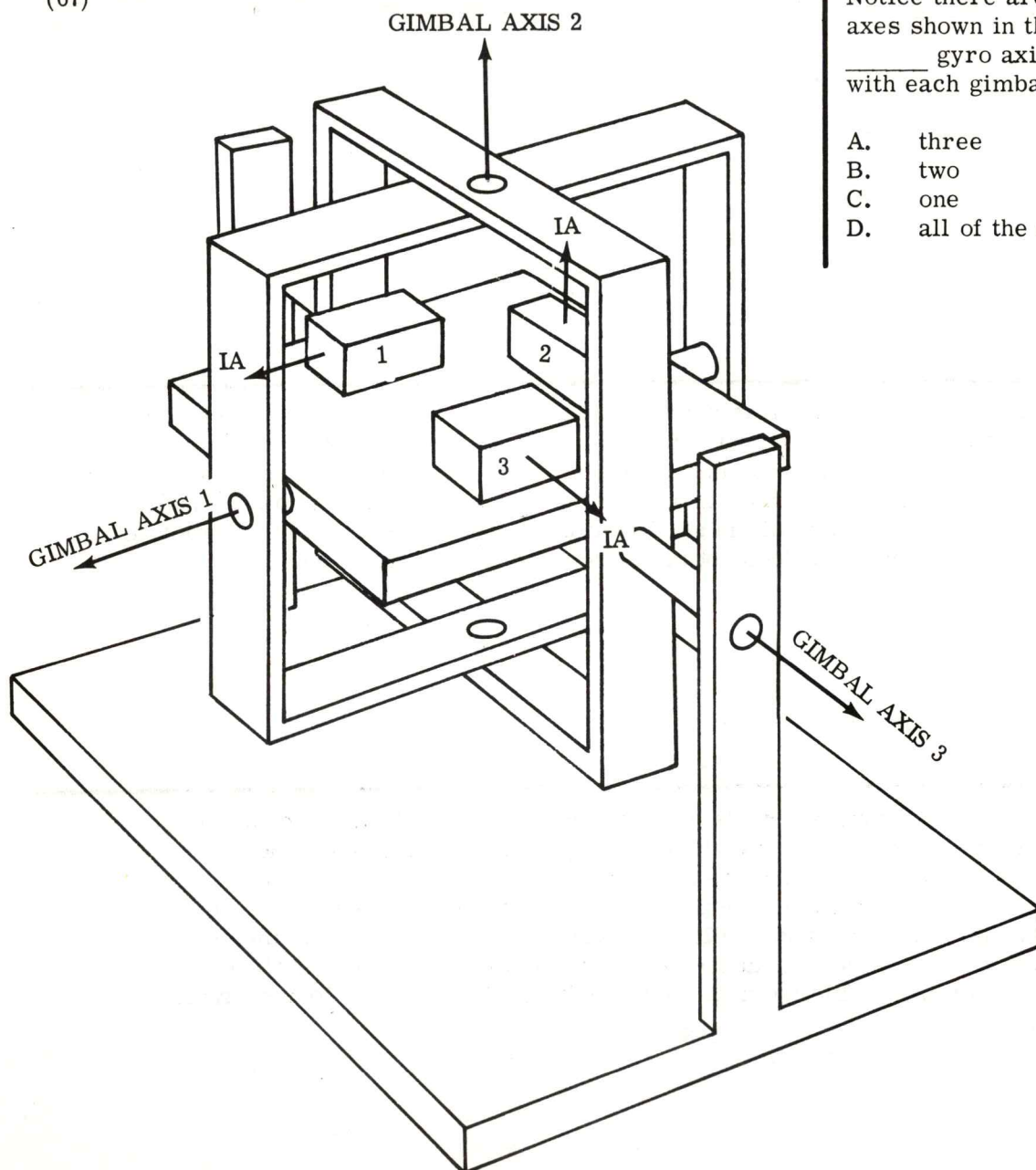
(66)



Any rotational movement of the stable platform will be sensed by:

- A. one gyro.
- B. two appropriate gyros.
- C. all gyros.
- D. one gyro or a combination of gyros.

(67)



Notice there are three gimbal axes shown in the illustration, _____ gyro axis (axes) align with each gimbal pivot point.

- A. three
- B. two
- C. one
- D. all of the above

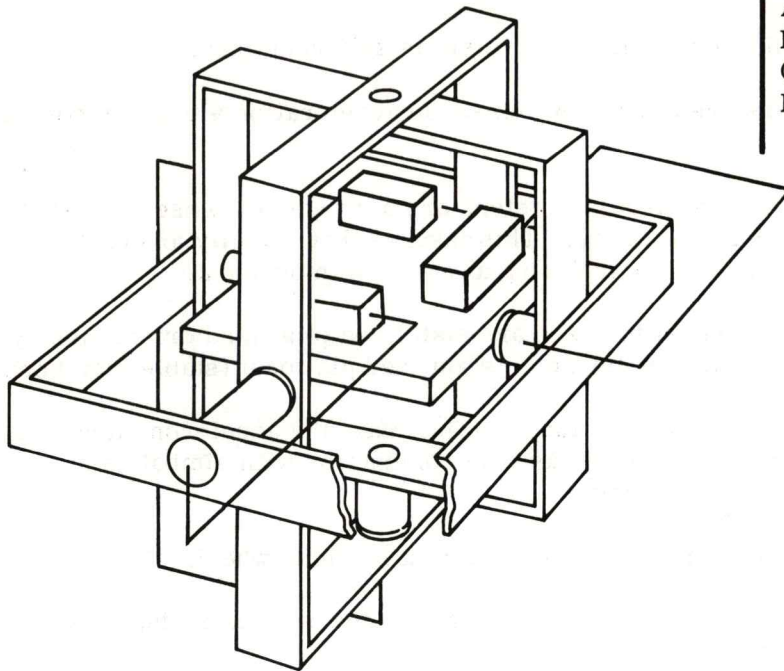
TURN SELECTOR TO POSITION 9

- (68) The associated loops for the stable member are the same as that explained for gyro 1 and gimbal 1. There is a DC torque motor mounted at one end of each gimbal axis so that when any gyro has an input rotation the appropriate gimbal torque motor will drive to reposition the stable member.

-
- (69) We consider the stable member as being completely stable when in reality the stable member must move a slight amount before the gyros can detect and correct the movement. It is important to realize that the quality of the gyros and associated components determine the overall stability of the stable member. With high quality components the reaction time of the stabilization loop is so fast that for all practical purposes the stable member does not move from the original position.

-
- (70) We have now a fully developed stable member on which we will later mount our accelerometers. Don't forget that the sole purpose for the gyros and the associated equipment was to provide a stable mounting for the accelerometers. In fact, if it were possible to develop frictionless bearings at the gimbal pivot points we would not need gyros at all. The only reason that the stable member would rotate is by friction drag at the pivot point as the vehicle moves about. Again, if there were no friction then we wouldn't find it necessary to have gyros.

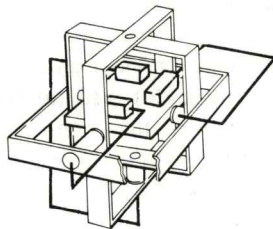
(68)



The function of the stabilization loops is to reposition the stable member when the gyros sense:

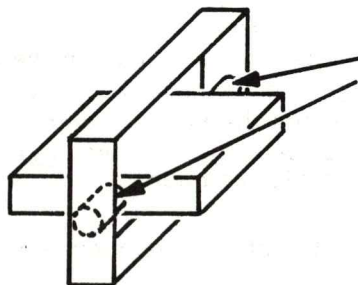
- A. rotational input.
- B. acceleration.
- C. precession.
- D. none of the above.

(69)



The prime function of the stabilization loops is to insure that the stable member doesn't change its orientation. This provides an ideal base for us to mount accelerometers.

(70)



If we had frictionless pivot supports, we would not have to insure that the platform acted as a stable member, as the gimbals were moved because of vehicle movement, the stable member would remain stable.

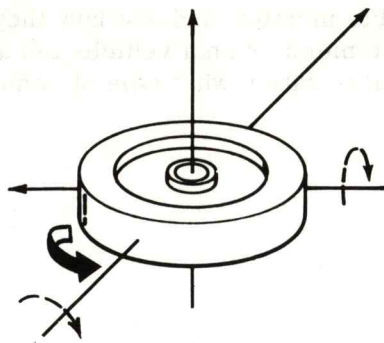
TURN SELECTOR TO POSITION 10

(71) REVIEW

In a few moments we will mount the gimbaled stable member on a vehicle and observe how it reacts to motion, but first a short review might be appropriate.

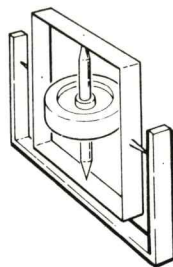
1. An inertial guidance/navigation system is self-contained.
2. Accelerometers are devices which sense acceleration along a particular input axis.
3. In a system, several accelerometers are arranged to sense acceleration in a three dimensional array. This insures that velocity and distance can be calculated as they occur during any vehicle movement.
4. The acceleration sensitive axes are stabilized to a fixed orientation by mounting the accelerometers on a stabilized platform (stable member).
5. The stable member has one function; maintain the accelerometers in a fixed orientation. Gyros are used in conjunction with gimbals and a stab loop to accomplish this.
6. We know that the gyro takes the form of a spinning wheel.
7. The axes normally associated with a gyro are: spin axis, input axis and output axis.
8. When a rotational input is applied about the input axis of a spinning gyro wheel, it reacts by rotating (precessing) about its output axis.
9. The right hand rule is used to determine the positive direction of an axis (really a vector representing a rotational quantity).
10. To readily determine the direction of precession of a gyro, we used the memory jogger (SPIN into IN), i. e. , if we can determine the + end of the input axis due to an input and we can determine the + end of the spin axis due to wheel rotation, then "SPIN into IN" (+ spin axis rotated toward the + input axis) provides the direction of precessional rotation about the output axis.
11. The frame which supports a gyro wheel is called a gimbal. The output axis is defined as passing through the gimbal pivot points.
12. To use a gyro in the stabilization process we mount a signal generator (potentiometer) on the output axis pivot such that when the gyro precesses (indicating an input rotation) a signal is generated. This signal is applied to a torque motor which can reposition the stable member. This arrangement is provided in three dimension, by three gyros, loops and gimbals to support the stable member.
13. The stabilization loops insure that the stable member is isolated from vehicle motion.
14. If a platform could be designed using frictionless pivots at the support points of the gimbals, we would have no need for the stabilization loops.

(71)



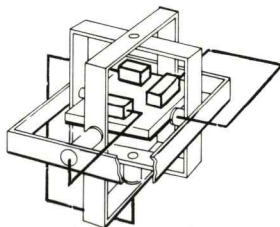
The function of providing a stable platform (stable member) is to:

- A. give a practical need for the stabilization loops.
- B. support the gimbal.
- C. provide a reference to mount accelerometers on.
- D. none of the above.



By using three gyros with their input axes _____, the system can sense any rotational input on one or more gyros.

- A. parallel
- B. orthogonal
- C. in line
- D. intersecting



When an output signal is generated by the potentiometer of one of our gyros, it:

- A. is used to drive the other gyros.
- B. is used to steer the accelerometer.
- C. causes the gyro to stop.
- D. is used to stabilize the stable member.

A rotational input about the input axis of a gyro causes it to:

- A. increase wheel speed.
- B. precess about its spin axis.
- C. rotate in a specific direction.
- D. precess about its output axis.

TURN SELECTOR TO POSITION 11

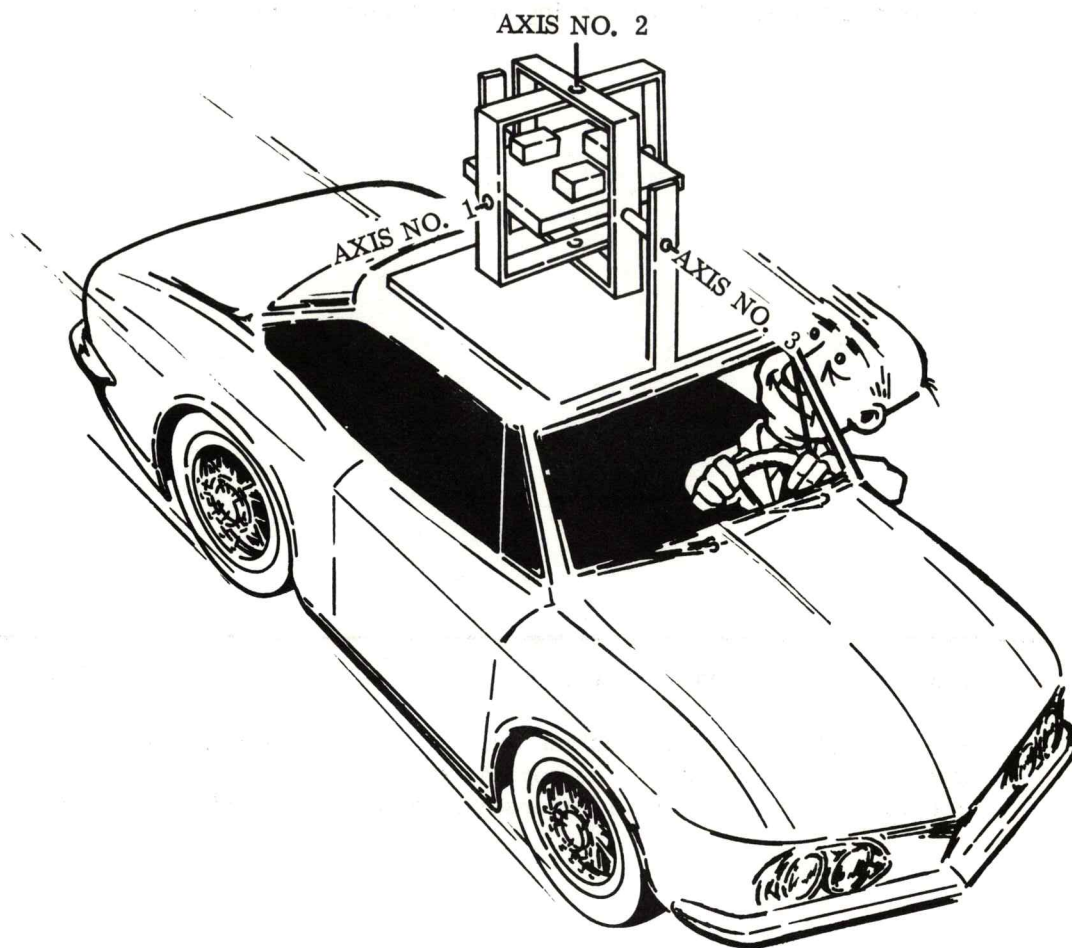
- (72) Shortly we shall mount accelerometers on the stable member and see how they function, but first we will mount the gimbal supported stable member on a vehicle and apply what we know about its operation. You can see in the illustration what type of vehicle we shall use.

-
- (73) Given the following situations and the illustration to the right - tell what gimbal torque motor will drive:

- a. car just starting up a hill
- b. car making a banked left turn
- c. car accelerating on level ground
- d. car driving in flat circle
- e. car stops abruptly.

Write your answers here (answers are discussed in next frames).

(72)



TURN SELECTOR TO POSITION 1

(74) Let's answer the five questions in order:

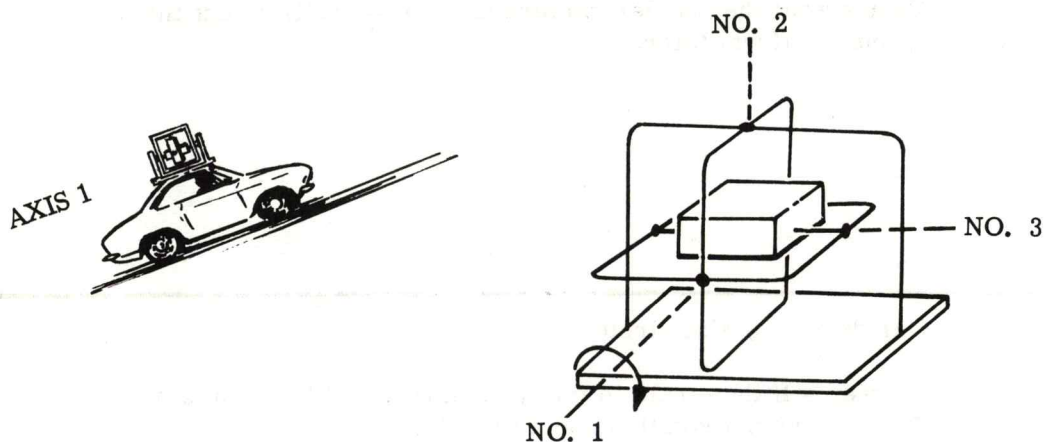
- a. Car going straight up a hill.

Answer - At the approach to the hill when the front of the car is being elevated, the motor on axis 1 will operate because all input rotation is about gyro 1 input axis. Once the car is on the hill and the front of the car is pointed up and not changing, no motors will operate.

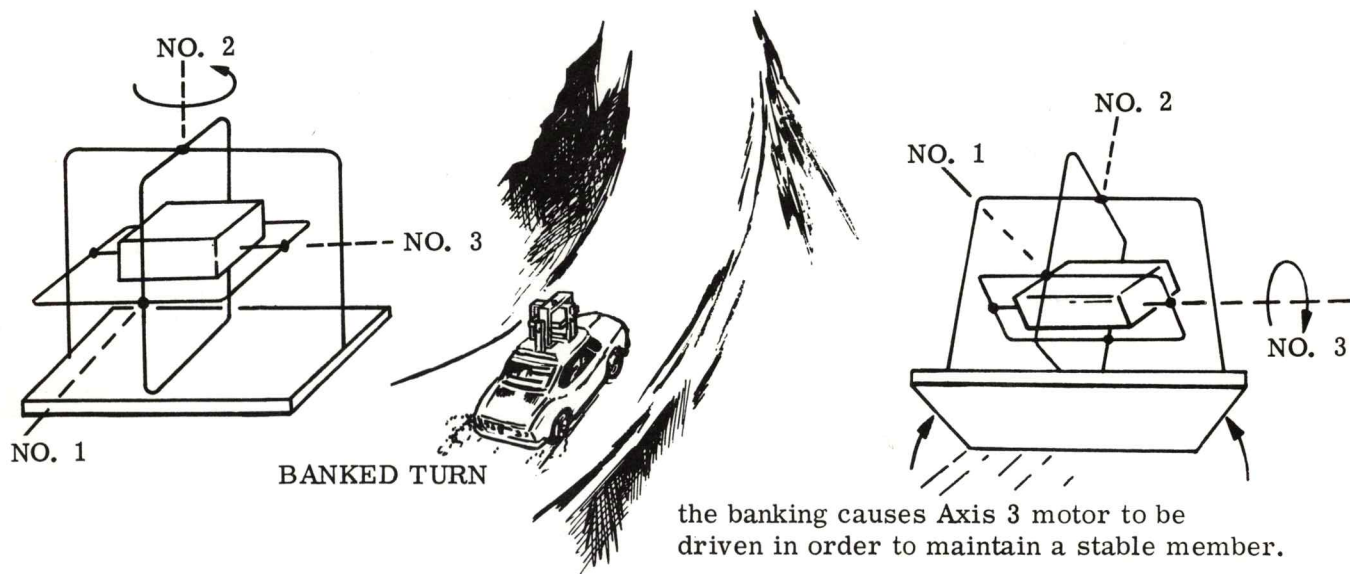
-
- (75) b. Car making a banked left turn.

Answer - Because of the banking the motor on axis 3 will drive. Because of the left turn the motor on axis 2 will operate. The combination of axis 2 and 3 motors will stabilize the stable member.

(74)



(75) The turning action causes Axis 2 motor to be driven.



TURN SELECTOR TO POSITION 2

(76) c. Car accelerating on straight and level.

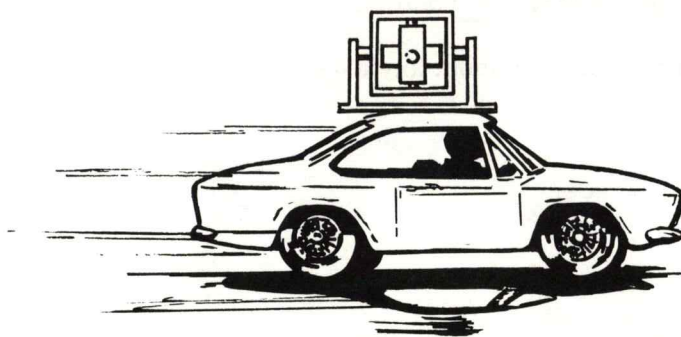
Answer - NOTHING NOTHING NOTHING

That's what the accelerometers are for -- we'll mount them on our platform later.

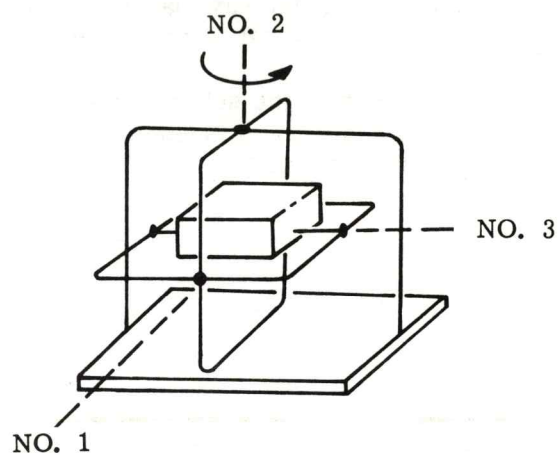
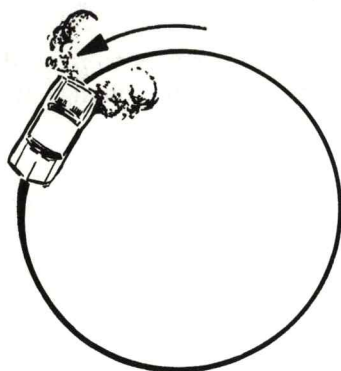
(77) d. Car driving in flat circle.

Answer - If the circle is flat all rotation will be about axis 2.
There is no net rotation about axes 1 or 3.

(76) WE HAVE BALANCED GYROS THUS NO NET ROTATION ABOUT ANY AXIS.



(77)



TURN SELECTOR TO POSITION 3

- (78) e. Car stops abruptly.

Answer - Again, NOTHING rotates.

There is no net rotation about any axis.

-
- (79) In summary, we can say that only if there is a net rotation about the axis which is doing the sensing, do we get a gyro output and thus a motor rotation.

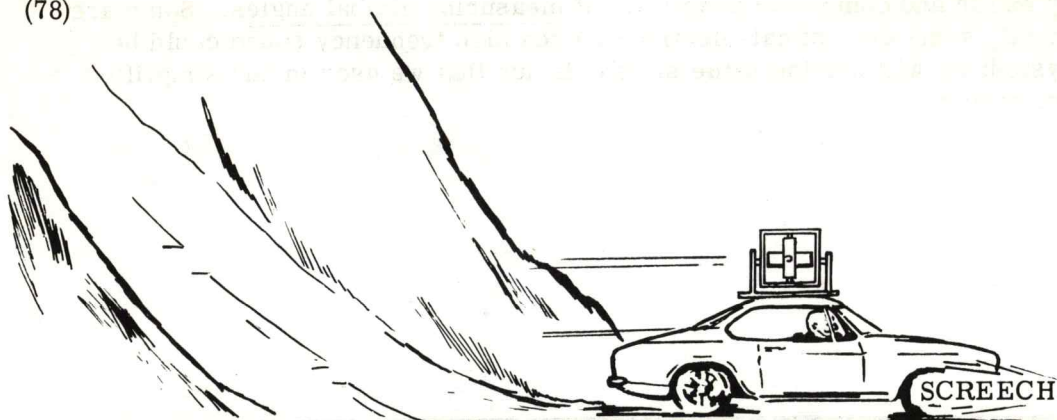
Keep in mind that the sole purpose of the gyros, gimbals and motors is to provide a stable platform that is independent of vehicle movement. It will never change its original orientation.

-
- (80) DETERMINATION OF ATTITUDE

As you put the stable member through its paces, did you get the feeling that maybe some useful information could be obtained from the equipment we have already developed? Did you consider that as the car went through the different maneuvers we could be receiving information about the car's heading with respect to the heading at the start? The orientation and heading of the car might be referred to as attitude. Let's discuss this point further.

-
- (81) Let's say that the car went up a 20° slope from level position. The stable member cannot move from the original orientation. The change in the car's attitude is 20° from the level position. In order for the stable member to remain level while the car is going up at 20°, gyro 1 sensed a rotation and torqued gimbal axis 1 through 20° of rotation. As the car continues up the hill, a 20° angle will exist between the original gimbal position and the present position. If we could measure gimbal angles then we would know the attitude (heading) of the vehicle, with respect to the original start attitude, at all times.

(78)



(79)

NEVER LET THE STABLE PLATFORM
LOSE ITS ORIGINAL ORIENTATION.

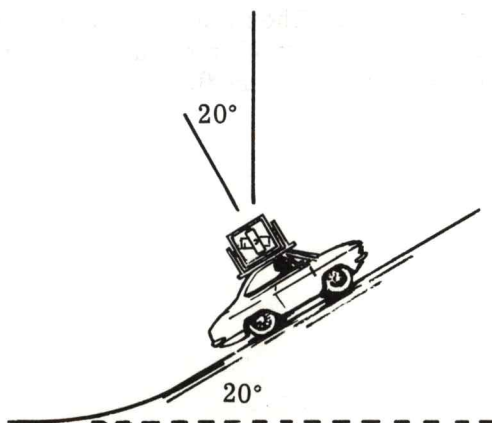
The gyros sense rotational movements, the stab loops correct and insure stability of the stable member. We are providing this stable platform as a reference to mount the accelerometers on.

- A. True
- B. False
- C. ----
- D. ----

(80)

"HEADING" AND "ATTITUDE" HAVE ESSENTIALLY THE SAME CONNOTATION
.....THE DIRECTION IN WHICH WE'RE POINTED.

(81)



As the vehicle changes position, the gimbals are moved to maintain the reference platform. If we could measure the amount of gimbal movement we could relate this to vehicle _____.

- A. acceleration
- B. speed
- C. attitude
- D. all of the above

TURN SELECTOR TO POSITION 4

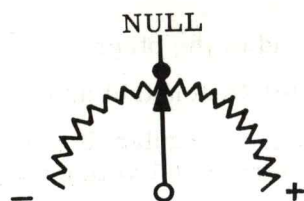
- (82) There are many exotic and complicated methods of measuring gimbal angles. Some are electro-mechanical, some are optical-electrical, even high frequency sound could be used. In our system we will use the same simple device that we used in our simplified gyros - a potentiometer.

-
- (83) We will need three potentiometers (one for each gimbal axis). To identify them we will call them attitude detectors and further identify them by attaching the number of the gimbal axis that is being monitored, thus - attitude detector 1, 2 and 3.

-
- (84) The point contactor will be attached to one gimbal while the wire coil will be attached to the adjacent gimbal. Since we are interested in relative movement of one gimbal with respect to the other, it doesn't make any difference which gimbal receives the pointer or wire coil.

-
- (85) The placement of the attitude detectors is critical. They must be placed on the gimbals so that when the adjacent gimbals are perpendicular to each other the attitude detectors have a zero output (the pointer is centered).

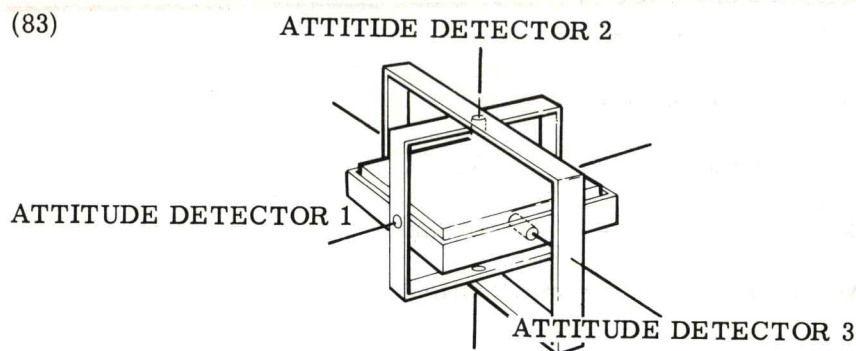
(82)



Before when we used a potentiometer as a signal generator, the signal generated provided information in terms of _____ and _____ regarding rotational inputs.

- A. magnitude - direction
- B. volts - amps
- C. up - down
- D. pressure - magnitude

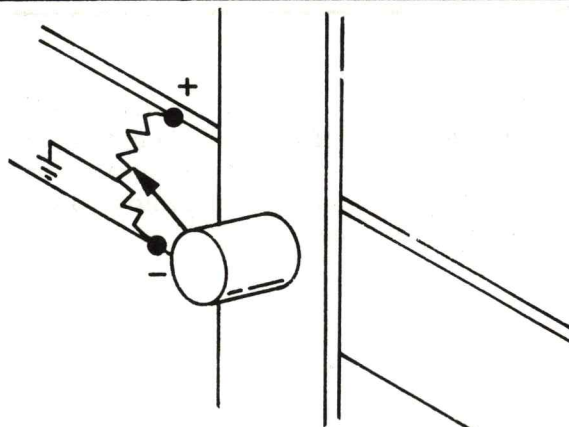
(83)



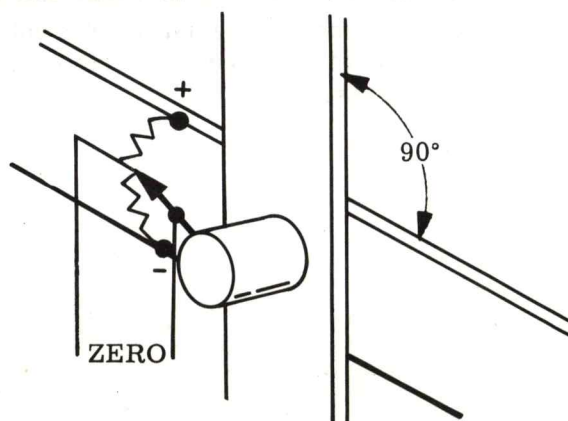
It is the function of the attitude detector to provide information indicative of:

- A. acceleration.
- B. gyro movement.
- C. gimbal movement.
- D. none of the above.

(84)



(85)



TURN SELECTOR TO POSITION 5

(86) There are certain criteria that must be assumed to be inherent in the design of these attitude detectors. They are:

1. The potentiometer is linear from one end to the other.
2. The voltage supplied to the potentiometer is constant and exact.
3. A scale factor exists to correlate voltage to angular displacement (degrees). For simplicity we will assume a scale factor of 1 volt/degree.

If +5 volts were read at the attitude detector output then there would be a +5° displacement of the gimbals from the perpendicular position.

(87) By now you should have a pretty good feeling for:

1. What is the job of an accelerometer.
2. Why we need a stable member.
3. How we mechanize gyros to provide a stable member.
4. Where and how we can obtain attitude information.

(88) THE ACCELEROMETER

We are now ready to go back and take a look at how the accelerometer measures acceleration. We will develop a simplified accelerometer - keep in mind that actual accelerometers are much more accurate and complicated, but the underlying principle of mechanizing Newton's second law is almost always the same, no matter what type accelerometer is used.

(89) In our discussion of accelerometers, we will be using the symbol "g". This symbol represents the amount of acceleration that a body on earth experiences due to the attractive force of gravity ($g = 32 \text{ ft/sec}^2$).

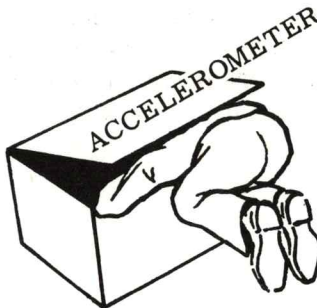
(86)

THE ATTITUDE DETECTORS ARE ACCURATELY SCALED TO PROVIDE VOLTAGE
OUTPUTS PROPORTIONAL TO ANGULAR DISPLACEMENTS.

(87) SUMMARY:

We will see shortly that an accelerometer mechanizes Newton's second law ($F = MA$) by measuring a force on a given mass thus indicating acceleration. To make the acceleration a directional quantity we isolate vehicle motion from the accelerometer sensing axes by using a stable member. This stable member uses gyros and gimbal DC torque motors to correct any stable member movement. The rotation of the gimbals "buffers" the vehicle movement. The gimbal angles are used then to detect vehicle attitude with respect to the null start position.

(88) WE ARE INTERESTED IN THE MECHANIZATION OF NEWTON'S SECOND LAW:



(89) "g" IS NOT GRAVITY

BUT

"g" IS THE ACCELERATION DUE TO GRAVITY.

Acceleration due to the attraction
of gravity on a body on or near
earth is:

- A. 32.2 ft/sec²
- B. 3.22 ft/sec²
- C. 980 ft/sec²
- D. 9.80 ft/sec²

TURN SELECTOR TO POSITION 6

- (90) It is interesting to note that a large number of people are not aware that Sir Isaac Newton was responsible for developing the relationship of force, mass and the acceleration due to gravity. Newton used the empirical data obtained from astronomers and developed the correlation of data which explained gravity.

-
- (91) He determined that there was a force between any two bodies (earth-sun, earth-moon, you-earth) and that this force was an attractive force that is proportional to the product of the two masses concerned, divided by the square of the distance between the centers of the two bodies.

-
- (92) Through mathematical manipulation it can be shown that the force on a body on earth is equal to the product of the bodies mass and "g". This is really Newton's second law, isn't it? $F = MA$, where the constant acceleration of a body at rest is "g" and is due to the force of gravity. Thus we say force due to gravity = mass of body on earth times acceleration due to gravity ($F_g = Mg$).

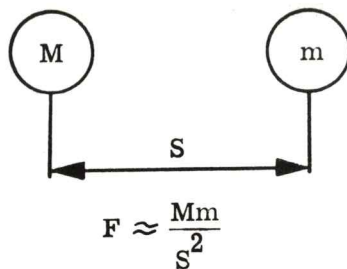
-
- (93) On the moon, the acceleration due to gravity is about one sixth of that on earth. This is because the mass of the moon is one sixth the mass of the earth. Thus the force due to gravity on the moon is $F = 1/6(Mg)$. Since this force is in a direction toward the center of the large mass (earth or moon) it is reasonable to say that a 600 pound weight on earth would only weight 100 pounds on the moon.

(90)

GOOD OL' ISAAC SURE DID HAVE SOME GOOD STUFF.



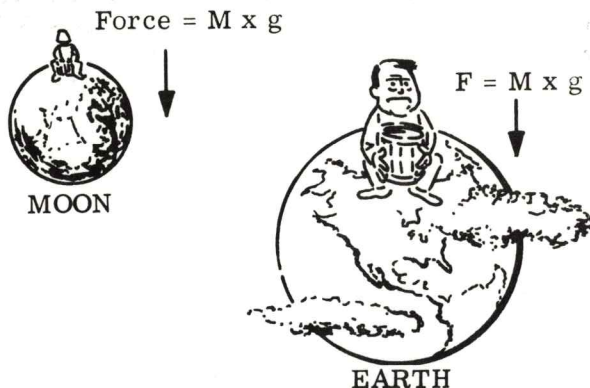
(91)



It appears that the attractive force between two masses is _____ proportional to the _____ distance between the masses squared.

- A. ----
- B. ----
- C. inversely
- D. directly

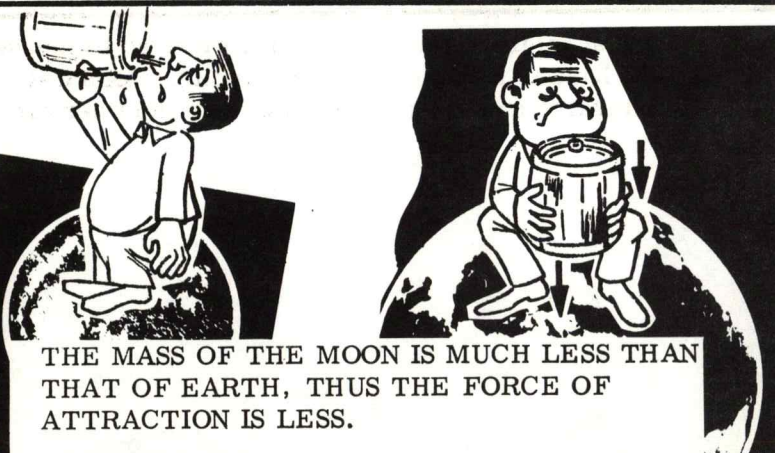
(92)



Newton's second law states the relationship of:

- A. mass and acceleration.
- B. gravity and the earth.
- C. acceleration and velocity.
- D. force and a product.

(93)



Because of the difference in mass, a body weighing 1800 lbs. on earth would only weight _____ on the moon.

- A. 200 lbs.
- B. 600 lbs.
- C. 300 lbs.
- D. 900 lbs.

TURN SELECTOR TO POSITION 7

- (94) Our accelerometer will detect "g" along with any other acceleration imposed on the accelerometer by the change in velocity of the vehicle. Keep in mind that "1g" is always present by virtue of the earth's gravitational force. Additional accelerations will be due to vehicle velocity changes.

-
- (95) Let's start building our accelerometer one piece at a time. To start with, we will need a spinning wheel similar to our gyro wheel. There will be one obvious difference in our wheel mounting technique as compared to the method used in gyros.

-
- (96) The accelerometer wheel will be displaced. In the illustration notice axis A-A'. The wheel can be raised or lowered about this axis. The wheel spins about axis B-B'. In the position shown, the wheel is at rest against the "L" shaped frame.

-
- (97) So far we haven't done anything with the accelerometer, and even if we tried to measure an acceleration - it wouldn't work. We have to add one more pivot point. Axis C-C' shows the third pivot. The "L" shaped frame can rotate about this axis in either direction.

(94)

$$1 \text{ g} = 32 \text{ ft/sec}^2$$

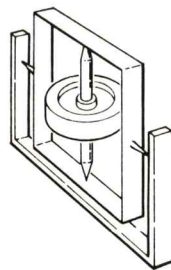
$$2 \text{ g} = 64 \text{ ft/sec}^2$$

$$3 \text{ g} = 96 \text{ ft/sec}^2$$

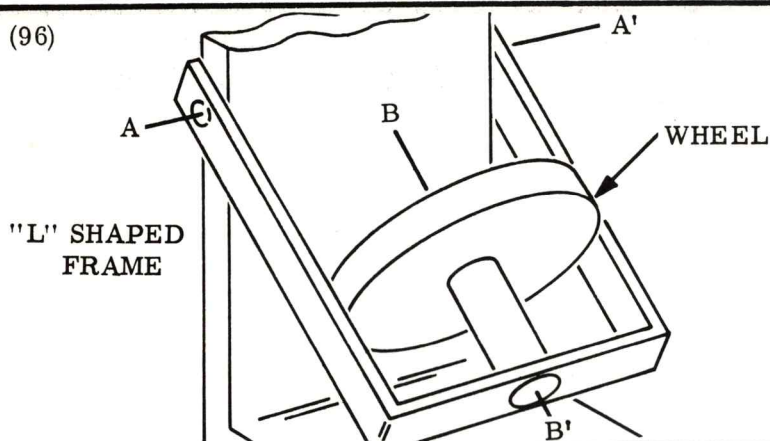
Accelerometers will sense change in vehicle velocity and also the acceleration of:

- A. Newton.
- B. gravity.
- C. force.
- D. weight.

(95) WHEEL MOUNTING ON THE ACCELEROMETER WILL BE DIFFERENT.



(96)

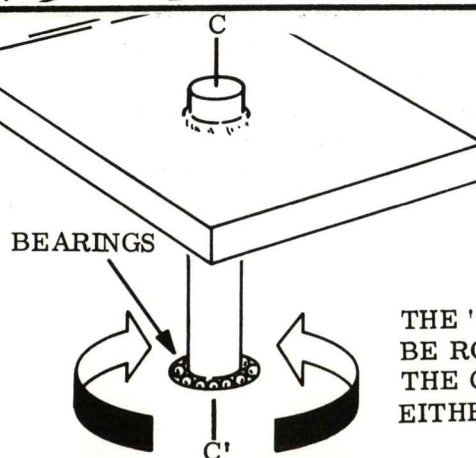


The wheel is mounted to pivot about axis A-A'. This is due to mounting the wheel such that there is a/an _____ condition about A-A'.

- A. balanced
- B. spinning
- C. unbalanced
- D. reverse spin

(97)

"L" SHAPED FRAME



THE "L" FRAME CAN BE ROTATED ABOUT THE C-C' AXIS IN EITHER DIRECTION.

TURN SELECTOR TO POSITION 8

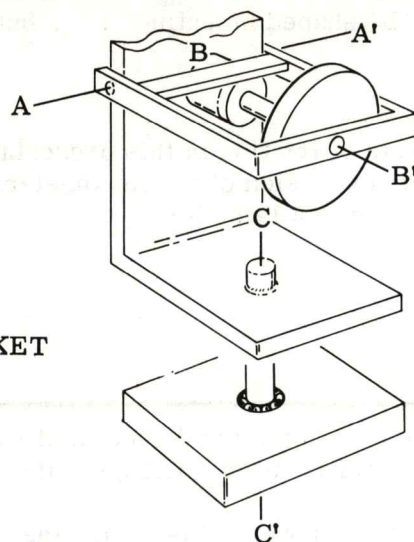
- (98) Let's take a look at the accelerometer which is, for the most part, complete. Study the illustration and identify the axis about which the various parts can move. The wheel rotates about axis B-B'; the wheel bracket pivots about axis A-A' and the entire L shaped frame is able to rotate about axis C-C'.

-
- (99) Notice that the weight of the wheel in essence forms a pendulum which can be displaced about axis A-A'. When the wheel is not rotating, gravity will force the wheel down into its lower most position illustrated in frame 96.

-
- (100) When the wheel is spinning and axis B-B' is horizontal, the situation is altered. Gravity still tries to force the spinning wheel down. But due to the gyros precession it will not fall down like it did with a stationary wheel. What will happen?

-
- (101) We learned that in gyros a rotation about the input axis causes a proportional rotation about the gyro's output axis. We have an unbalanced gyro in our accelerometer. That is, the input rotation about axis A-A' is caused by gravity exerting a force on the unbalanced wheel. As the wheel attempts to drop, due to the force of gravity, the spin axis (B-B') is displaced downward. A gyro will not allow this to happen, will it? As a result, rotation (which is proportional to the attempted rotation about axis A-A') will be introduced about axis C-C'.

(98)



WHEEL

"L" BRACKET

The entire "L" bracket can be rotated about axis C-C'.

- A. ----
B. ----
C. False
D. True

(99)

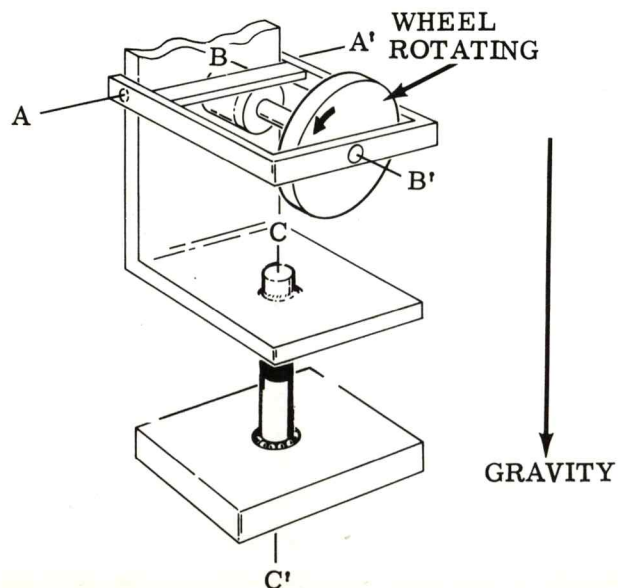
The wheel spins about axis B-B'.

- A. Cannot be determined.
B. False
C. True
D. None of the above.

(100)

When the wheel is not spinning (in the position shown), the wheel immediately will _____ due to gravity.

- A. precess about A-A'
- B. fall downward about A-A'
- C. rise upward about A-A'
- D. none of the above



Gravity causes the spinning wheel to drop about axis A-A'

This causes axis B-B' to be displaced. The gyro will precess about C-C' and attempt to stabilize axis B-B'.

(continue to next frame)

TURN SELECTOR TO POSITION 9

- (102) Without actually seeing this happen, it is somewhat difficult to believe that the wheel will not fall down and "grind to a halt" against the "L" shaped mounting. . . . but it won't.

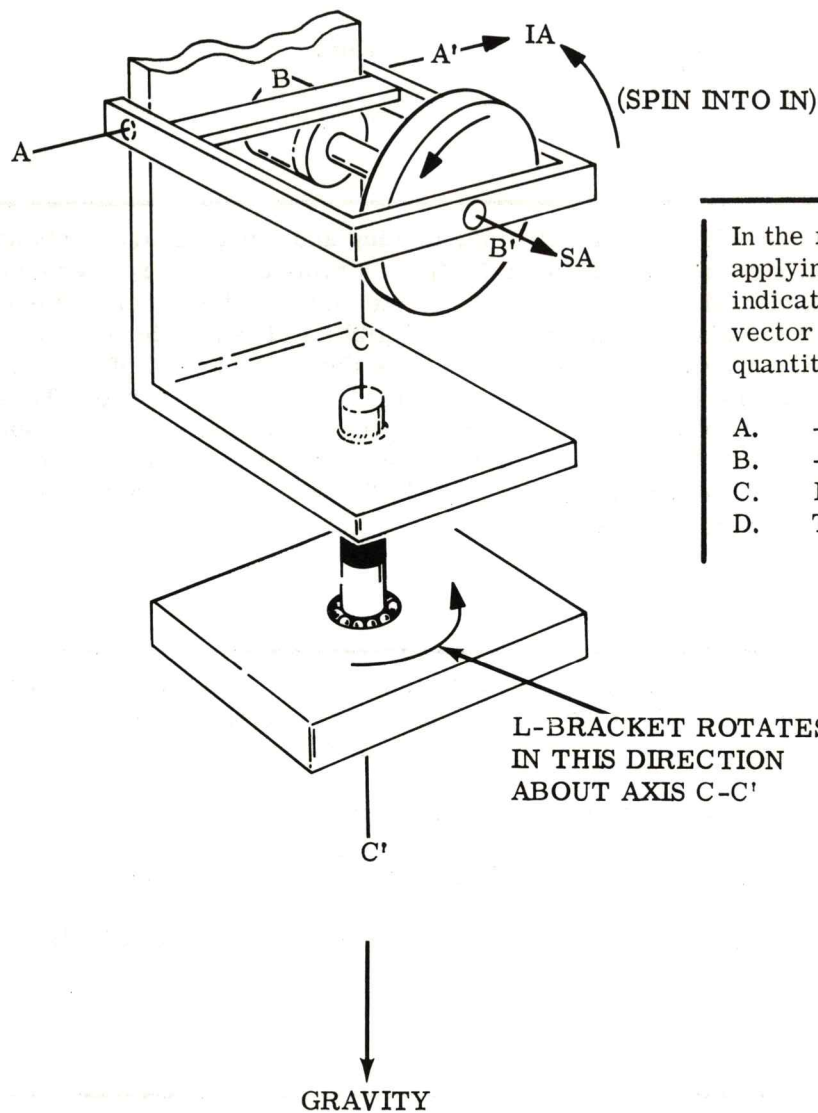
NOTE: We have deliberately neglected the effects of friction in this presentation. Our accelerometer is an idealized unit. A complete discussion of accelerometers and the effects of friction on these accelerometers is found in a later text.

-
- (103) We can use the right hand rule (SPIN into IN) to determine the direction of rotation about axis C-C', assuming we know the direction of wheel rotation. Let's try it.

Assume the wheel is rotating in the direction shown. This means that the positive spin axis is indicated by the arrowhead. (Fingers of right hand point around wheel in direction of rotation - thumb points to the right.) Gravity tends to pull the wheel down about axis A-A'. Applying the right hand rule we see that the positive input axis is into the paper. To determine the rotation about C-C' we rotate the positive spin axis into the positive input axis thus the indicated rotation (counter clockwise looking from the top) about axis C-C'.

(102)

(103)



In the right-hand rule we are applying here, the thumb indicates the positive end of a vector representing a rotational quantity.

- A. ----
- B. ----
- C. False
- D. True

TURN SELECTOR TO POSITION 10

- (104) By virtue of the "right hand rule" if we were to lift the spinning wheel so as to introduce a rotation about axis A-A', then the rotation about axis C-C' would be clockwise as observed from the top -- right?

RIGHT!

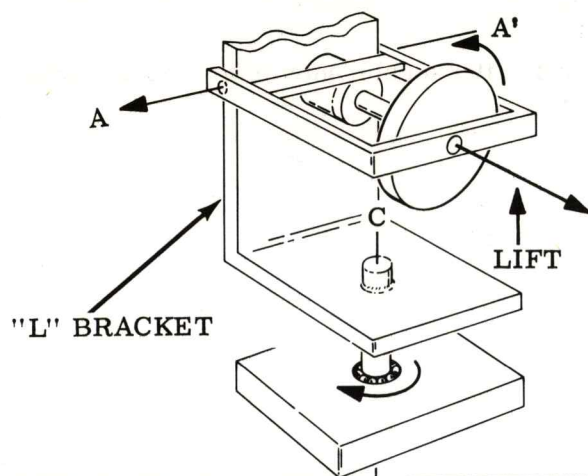
-
- (105) Now that we have our accelerometer spinning, turning and, in general, working. Let's find out what it's capable of telling us! Keep in mind that we are mechanizing Newton's second law ($F = MA$). The mass (M) is the mass of the wheel. (We will consider the mass of the wheel mounting arm negligible.) The acceleration (A) is the acceleration due to gravity and later will include the acceleration of the vehicle. With a mass and an acceleration, we have, according to Newton, a force. This force tends to displace the wheel's spin axis (B-B') about axis A-A'. The result is a rotation about axis C-C'. Thus the greater the acceleration on the given wheel mass, the greater the rotation about axis C-C'. We seem to be on the right track for measuring acceleration.

-
- (106) It is not the intent of this book to teach you detailed accelerometer theory. It is, however, the intent of this book to give you some understanding of how acceleration is sensed by an accelerometer. You should understand that:

1. Gravity will cause the accelerometer to react.
2. Any additional acceleration will also cause the accelerometer to react.
3. Only an acceleration which has a component along axis C-C' will be sensed by the accelerometer.

-
- (107) If we understand the basic operation of this gyro accelerometer, then we know that something is still missing. What do you think it is?

(104)

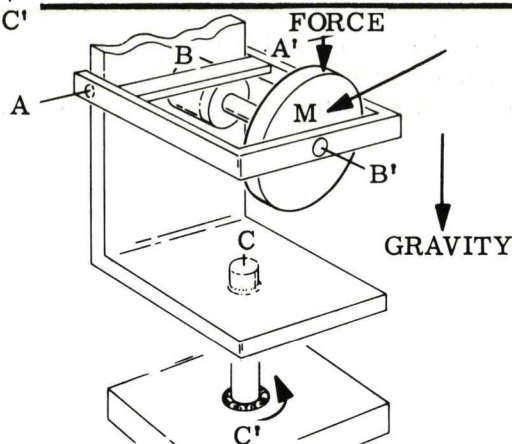


Gyro precession is the rotational force which causes the "L" bracket to rotate about axis C-C'.

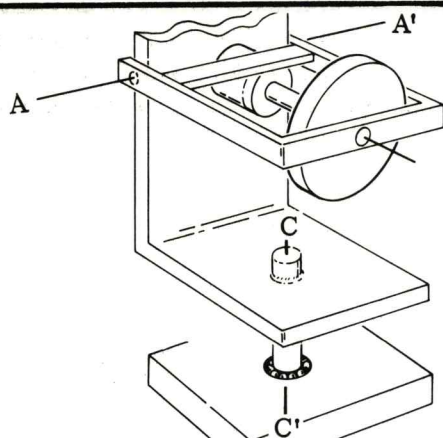
- A. It cannot be determined.
- B. Not enough information is given to determine the answer.
- C. True
- D. False

(105)

$$F = MA$$



(106)



ONLY AN
ACCELERATION
ALONG THIS
AXIS WILL BE
SENSED!!!

Notice that our device is acceleration sensitive along the C-C' axis. This is because the _____ is along this axis and about axis A-A'.

- A. precession
- B. gyro
- C. balance
- D. unbalance

(107)

WE HAVE A WORKING MODEL OF AN ACCELEROMETER, WHAT IS STILL MISSING?

(Continue to the next frame.)

TURN SELECTOR TO POSITION 11

- (108) Your right! We need some method of allowing the accelerometer to "tell us" what type and how much acceleration it is sensing.

-
- (109) We know that the L bracket will rotate at a rate which is indicative of the acceleration being felt by the spinning wheel. In order for this rotation to be useful we must develop a method of monitoring the rotation of the "L" bracket.

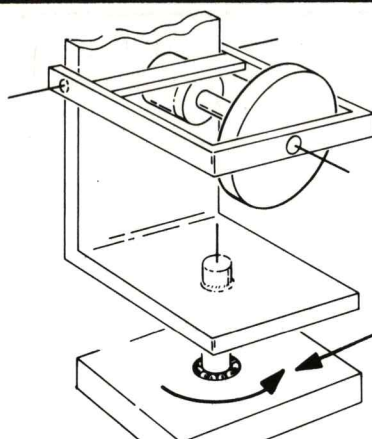
-
- (110) In our system we will place eight salient areas (bumps), equally spaced, around the periphery of the monitoring plate. Adjacent to the monitoring plate a counter is positioned. Each time a salient area passes the counter, the counter is incremented (stepped).

-
- (111) We have agreed that the rate of rotation of the monitoring plate is indicative of the acceleration that is being experienced by the spinning wheel. The counter will indicate, by incrementing, the rotation through each angle θ .

(108)

WE WILL NEED SOME SORT OF MONITORING DEVICE ON OUR ACCELEROMETER.

(109)

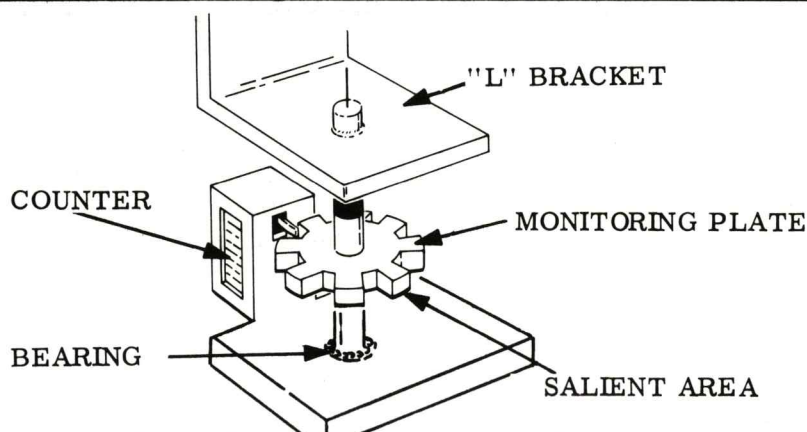


The rotation of the "L" bracket:

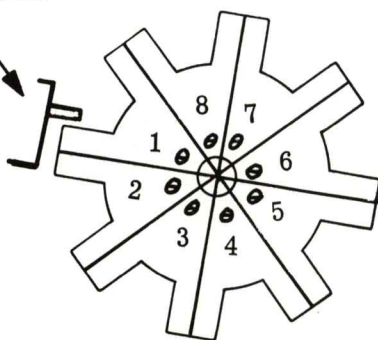
- A. indicates direction.
- B. indicates acceleration.
- C. indicates gyro position.
- D. rate of distance change.

THE RATE OF ROTATION ABOUT C-C' IS INDICATIVE OF AN ACCELERATION.

(110)



(111) COUNTER



Notice in the illustration provided, each time the counter is struck by a salient pole, the monitoring plate has progressed through:

- A. an angle .
- B. a precessional limit.
- C. 180°.
- D. all of the above.

TURN SELECTOR TO POSITION 1

- (112) If we tabulate the number of counts accumulated over a specific time we then have the angular rate of rotation. This rate of rotation is directly related to acceleration.

-
- (113) The rate of rotation of the "L" bracket is directly proportional to the acceleration that the displaced wheel experiences. For a high acceleration, a high turning rate results and a rapid accumulation of counts results. We can say that for a specific acceleration, over a specific time period, a specific change in velocity will occur. To make the counter's display meaningful we must introduce what is known as a scale factor.

-
- (114) A scale factor is a conversion "tool". It will tell us the value of each count from the counter. Our scale factor will be, "an acceleration of 1g (32 ft/sec²) results in one revolution of the L bracket in one second". With eight salient areas on our monitoring plate we know that each time we accumulate eight counts we have made one revolution with the L bracket. If we accumulate eight counts in one second we know we have experienced an acceleration of 1 g (32 ft/sec²). If we agree that a specific acceleration results in a specific velocity and a specific number of counts (8 counts/g/sec) then the counts must tell us our velocity.

-
- (115) An example might help. An acceleration of 2 g's ($2 \times 32 \text{ ft/sec} = 64 \text{ ft/sec}$) is introduced for one second. Using our scale factor presented in frame 114 we know the "L" bracket will turn around two times per second as a result of this acceleration. The velocity resulting from this acceleration is 64 ft/sec ($V = at = 64 \text{ ft/sec}^2 \times 1 \text{ sec} = 64 \text{ ft/sec}$). With eight counts per revolution, we would have sixteen counts displayed in one second. It follows then that each count displayed on the counter must be an increment of velocity and actually is equal to $4 \text{ ft/sec/count} = \text{total velocity} / \text{number of counts} = 64 \text{ ft/sec} / 16 \text{ counts}$.

(112)

L BRACKET ANGULAR RATE
IS DIRECTLY RELATED TO
ACCELERATION.

Once we tabulate the counts per second, we will have a value which can be related to:

- A. acceleration.
- B. velocity.
- C. distance.
- D. all of the above.

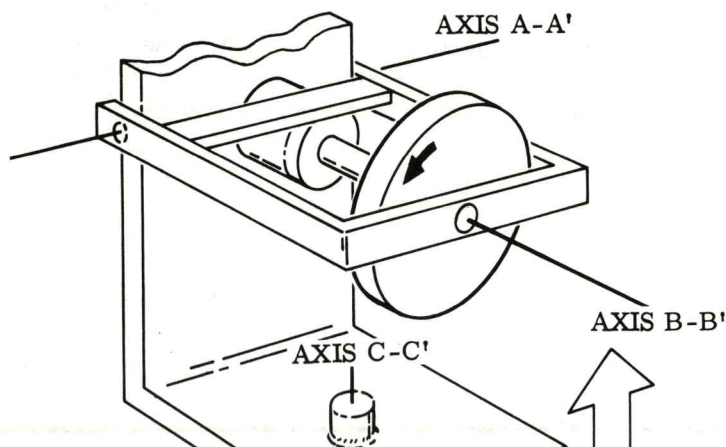
(113)

A COMMON TOOL FOR
DETERMINING THE
APPLIED ACCELERATION
TO A DEVICE OF THIS
TYPE IS CALLED SCALE
FACTOR.

When the number of counts/sec changes, we know that the _____ sensed has changed.

- A. acceleration
- B. distance
- C. attitude
- D. none of the above

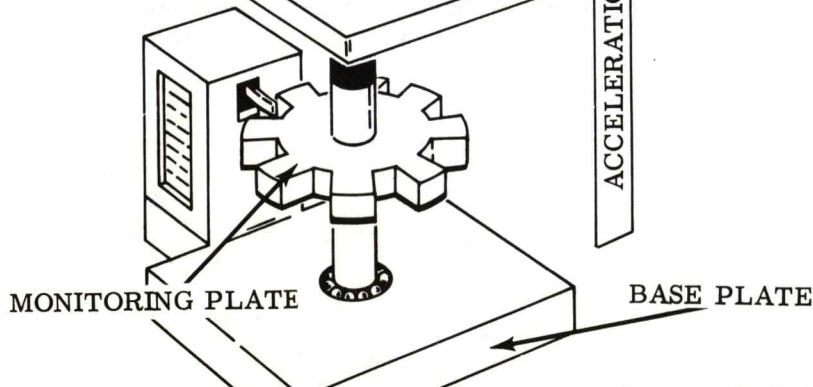
(114)



According to the scale factor information given in this frame, if 16 counts/sec were received from the accelerometer we would assume an acceleration of _____ g's is occurring.

- A. 1
- B. 3
- C. 2
- D. 4

(115)



TURN SELECTOR TO POSITION 2

(116) Let's put our accelerometer back in the black box we took it from. We know what's inside now so we can label the outside of the box with only the needed information. We must know:

1. Where axis C-C' is because this is the sensitive input axis.
2. We must have a reading of our accelerometer counts.

(117) We will place a device inside the box that will convert the accelerometer counts into electrical signals. These electrical signals will be routed to the computer for analysis.

(118) You recall that the data obtained from the accelerometer will be used to calculate velocity and distance. Our inertial guidance/navigation system will not use values of acceleration directly. It will use only velocity and distance information which is mathematically extracted in the computer from the accelerometer counts.

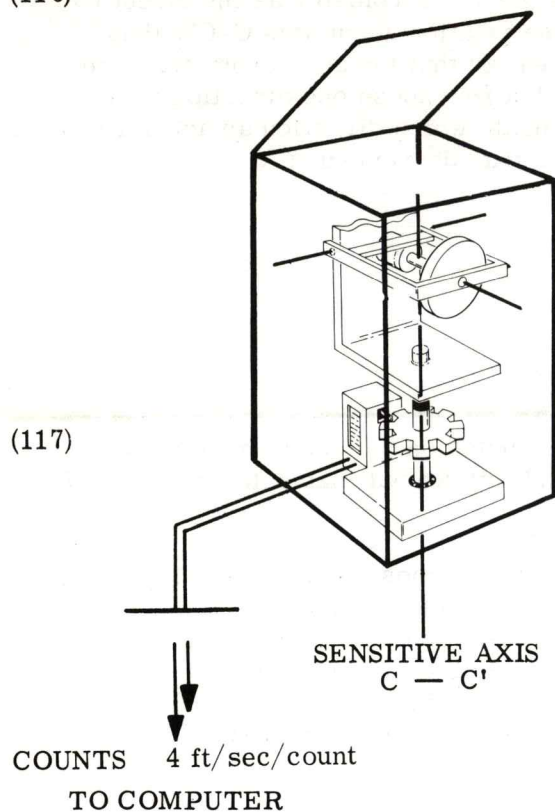
(119) Just as we had to mount three gyros orthogonally we will also mount three accelerometers on the stable member orthogonally (mutually perpendicular sensitive axes). We do this so that any acceleration in any direction will be sensed by one or more accelerometers.

(116)

When our gyro accelerometer is placed back in the box we had earlier (with an angle sensitive input axis) we now see that axis _____ is the input axis of the accelerometer.

- A. B-B'
- B. C-C'
- C. A-A'
- D. none of the above

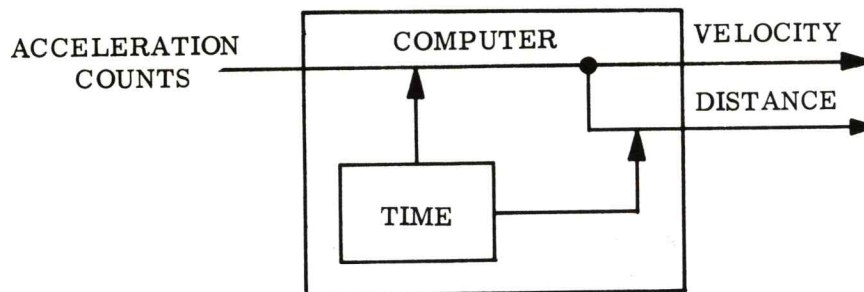
(117)



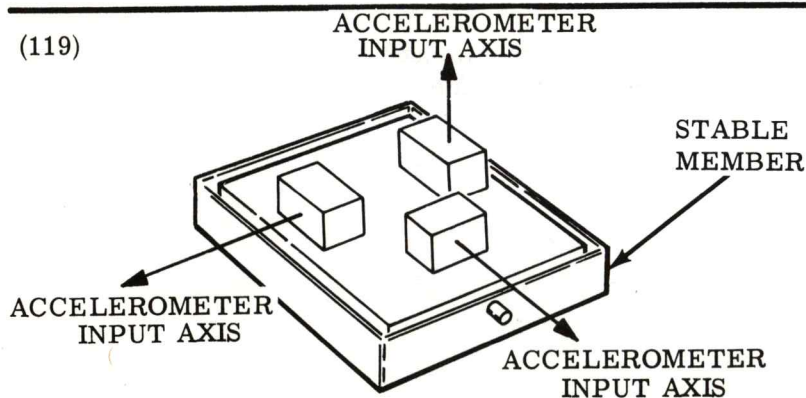
The counts developed by the accelerometer will be routed to the _____ for calculation of velocity and distance.

- A. counter
- B. gimbals
- C. computer
- D. all of the above

(118)



(119)



By mounting the sensitive axes of three accelerometers in an or orthogonal fashion, we will be able to sense acceleration experienced by the:

- A. accelerometers.
- B. stable member.
- C. none of these answers are correct.
- D. A and B are correct.

TURN SELECTOR TO POSITION 3

- (120) We have arbitrarily assigned a positive input axis of the accelerometer as the direction in which an acceleration must be to obtain a clockwise rotation about axis C-C', thus in the illustration you see arrowheads. We should realize that the accelerometers are equally sensitive in either direction along axis C-C' but we choose one direction as a positive input axis to provide a reference, and to indicate which direction an acceleration must occur, in order to increment the counter rather than decrement it.

-
- (121) In order for us to identify any given accelerometer mounted on the stable member we will assign a name to each accelerometer. For simplicity we will name them "forward", "side" and "up".

FORWARD ACCELEROMETER: That accelerometer whose input axis is directed in a specific direction and will maintain this orientation.

UP ACCELEROMETER: That accelerometer whose input axis is pointed away from the center of the earth at the time of departure (vertical).

SIDE ACCELEROMETER: That accelerometer whose input axis is perpendicular to both the UP and FORWARD accelerometers input axis and points to the right of FORWARD. (Nifty - eh!)

(122) REVIEW OF GUIDANCE/NAVIGATION CONFIGURATION

Let's consider the entire grouping of equipment we have built so far.

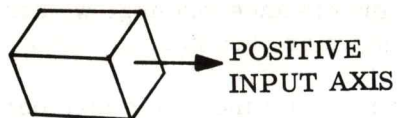
We have:

1. A stable member
2. Three gyros and three gimbals
3. Three accelerometers
4. One computer

Can you give a reason for having each of these four items?

Write your reasons below: (Answers are in next frame.)

(120)



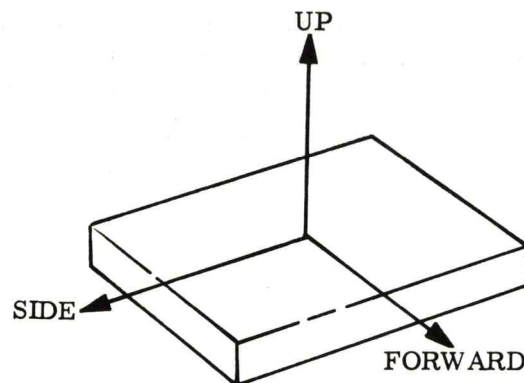
Remember, way back, we use a _____ system in order to maintain the accelerometer axes in a specific orientation.

- A. computer
- B. velocity measuring
- C. accelerometer
- D. stabilization

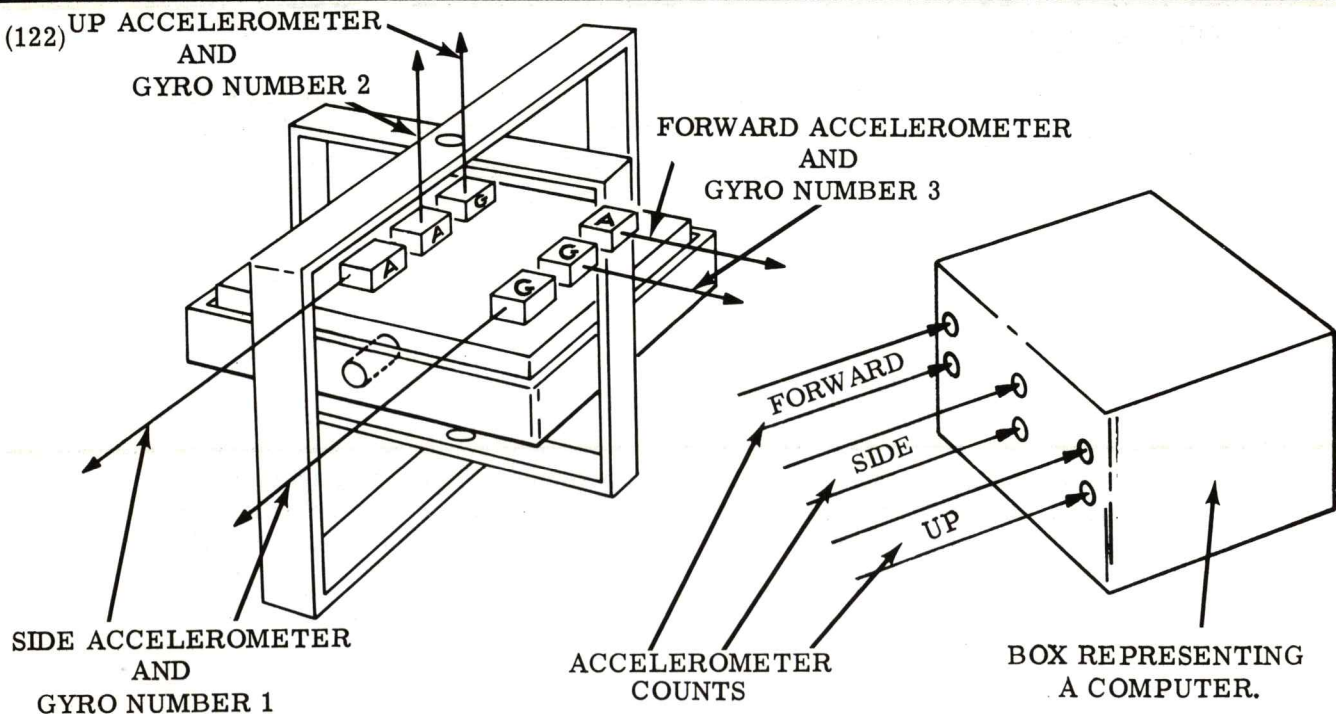
Positive accelerations increment the counter (increase)

Negative accelerations decrement the counter (decrease)

(121)



(122) UP ACCELEROMETER
AND
GYRO NUMBER 2



TURN SELECTOR TO POSITION 4

(123) By way of summary, let's answer the questions presented in the text of frame 122.

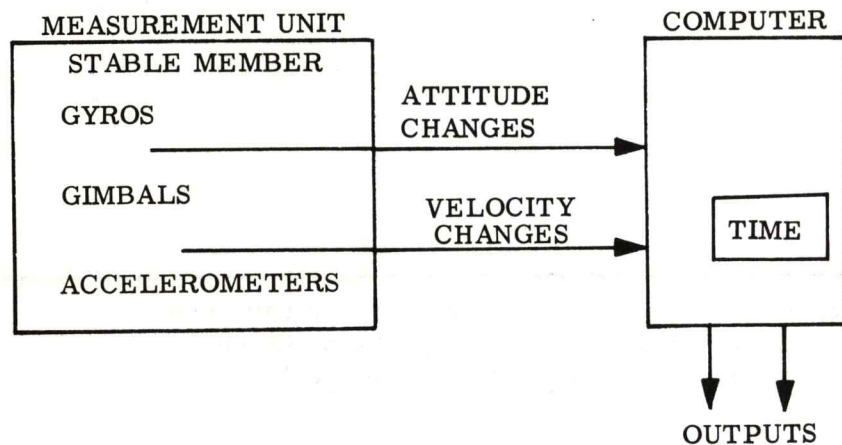
1. We need a stable member to give the accelerometers a directional quality so that when we develop velocity and distance readings we can identify where we are and in what direction we are heading.
2. The gyros are used as sensors to maintain the stable member independent of vehicle movement. The gimbals provide the means of three dimensional stabilization of the stable member.
3. The accelerometers mechanize Newton's second law and provide a measurement and indication of changes in velocity. The change in velocity information from each accelerometer is sent to the computer.
4. The computer keeps track of each accelerometer's counts and mathematically incorporates time in order to determine true velocity and distance in all three directions (forward, side and up). The computer will also monitor gimbal angles to determine heading (attitude) of the vehicle.

(124) THE MEASUREMENT UNIT

Notice that we have named the grouping of stable member, gyros, gimbals and accelerometers "measurement unit". From now on we will refer to the measurement unit as that unit which provides attitude and velocity-change information.

-
- (125) We haven't discussed what the computer will provide. We know it accepts the information from the measurement unit and it calculates the true velocity and distance in the "forward", "side" and "up" directions. So what does it do with the information?

(123)



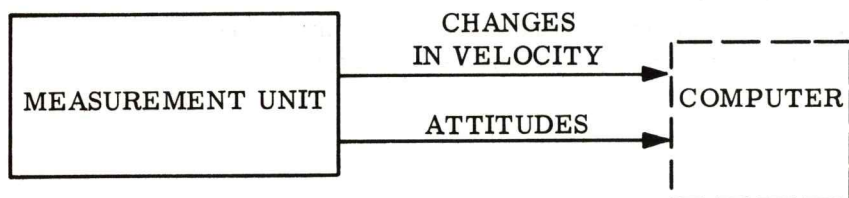
The accelerometers we have observed make direct use of Newton's second law, $F = MA$. The gyro wheel is unbalanced or displaced to cause an unbalance along the:

- A. input axis.
- B. spin axis.
- C. output axis.
- D. all three gyro axes.

In the inertial guidance/navigation system we are studying information representing attitude and _____ changes are sent to the computer.

- A. precessional
- B. distance
- C. velocity
- D. all of the above.

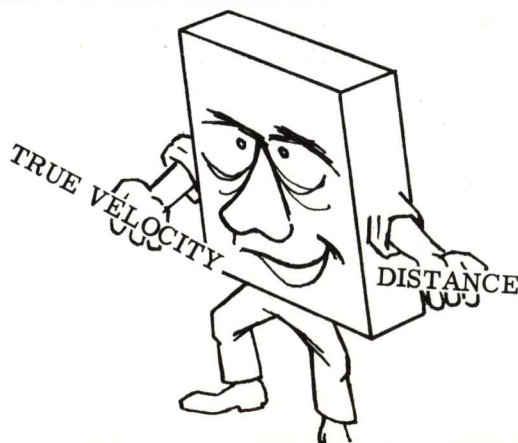
(124)



The "Measurement Unit" which provides attitude and changes in velocity to the computer will be made up of:

- A. gyros and a stabilization system.
- B. all of these answers are correct.
- C. accelerometers and associated signal generator.
- D. gimbals and attitude signal generators.

(125)



TURN SELECTOR TO POSITION 5

- (126) When an "all inertial guidance/navigation system" is used in a vehicle, the computer has values of velocity and distance placed in its memory prior to departure. These values that are stored in the computer represent specific parameters required for the vehicle to reach a specific destination. The computer can be thought of as a comparator of information.

-
- (127) The computer compares the actual data provided by the measurement unit to the ideal data which has been placed in the computer prior to departure. On the basis of this comparison the computer could issue steering signals and/or velocity change requirements.

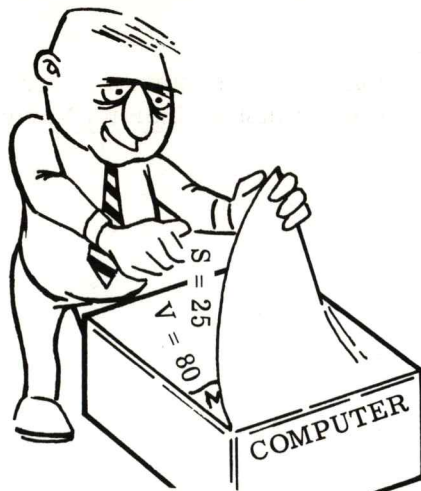
-
- (128) For the present we will be satisfied to know what the computers capabilities are. Not how we use them. Later in the text we will use the equipment we have built to guide us on some interesting trips. So. . . for now, let's assume that the computer is a comparator and that it can compare preloaded ideal information to the actual vehicle information obtained from the measurement unit.

-
- (129) Before we discuss the types of guidance profiles that our system is apt to encounter, it would be well for us to make some definitions.

FIRST: To navigate is to establish a position.

SECOND: To guide is to steer or direct.

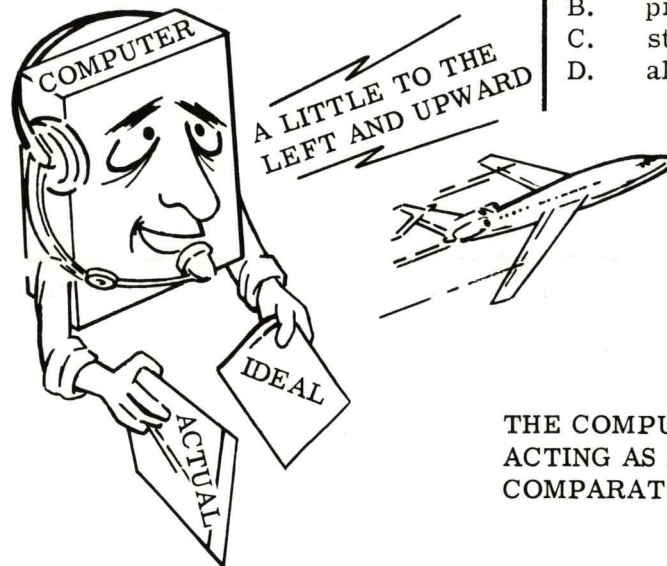
(126)



Actually the computer acts as a comparator of stored values against sensed values when solving the guidance/navigation problems.

- A. False
- B. True
- C. ----
- D. ----

(127)



In guidance the vehicle in which we have placed our guidance system, the computer will issue:

- A. verbal commands.
- B. precession pulses.
- C. steering signals.
- D. all of the above.

THE COMPUTER IS
ACTING AS A
COMPARATOR

(129) NAVIGATE - Establish a position.

GUIDE - To steer or direct.

TURN SELECTOR TO POSITION 6

- (130) On the basis of our definitions we can further analyze our system and see whether we can call it an Inertial Guidance/Navigation System or just an Inertial Navigation System.

-
- (131) If we call our system an Inertial Navigation System the only function required from the system is that it provides continuous information as to the vehicles position. In order for the system to do this, it must only know exactly where it started. It will, by measuring acceleration, determine distance. (The direction is attainable by virtue of original placement of our accelerometer input axis.) These distances accumulated in three directions are added to the original position thus indicating present position.

-
- (132) The displayed present position would be calculated by the computer and could be mechanized so that the readout was in miles, meters, latitude and longitude or whatever units are appropriate for the need.

-
- (133) In order for our system to be called a Guidance System, the system must have the capability of steering the vehicle. In order for the system to steer, it is imperative to have a destination to steer to. . . . isn't it? This may sound ridiculous, but a second thought will identify two things necessary for an Inertial Guidance System.

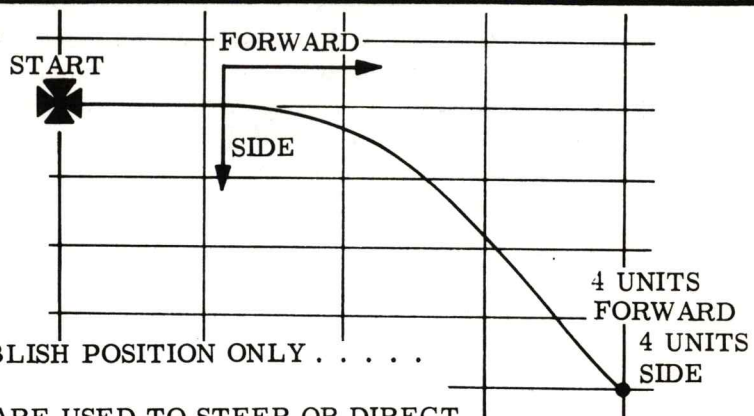
(130)

INERTIAL GUIDANCE/NAVIGATION

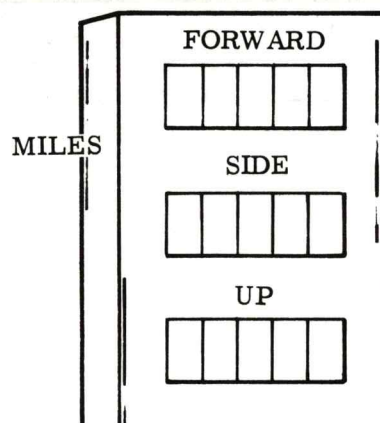
OR

INERTIAL NAVIGATION

(131) INERTIAL NAVIGATION SYSTEMS



(132)



Our Inertial Navigation System provides readouts which can be used to indicate present:

- A. position.
- B. time.
- C. gimbal attitude.
- D. precession.

(133) INERTIAL GUIDANCE MUST:

1. KNOW PRESENT POSITION
2. KNOW DESTINATION.

TURN SELECTOR TO POSITION 7

- (134) Inherent to the Inertial Guidance System is the capability of determining present position and comparing the present position with the position of the destination. On the basis of this comparison, steering signals from the computer will be sent to the vehicle.

-
- (135) So you see, that really there isn't such a thing as an Inertial Guidance System, Per Se. In order for the system to guide, it must meet the criteria for an Inertial Navigation System and, in addition, be able to issue corrective steering signals which will direct the vehicle to a defined destination.

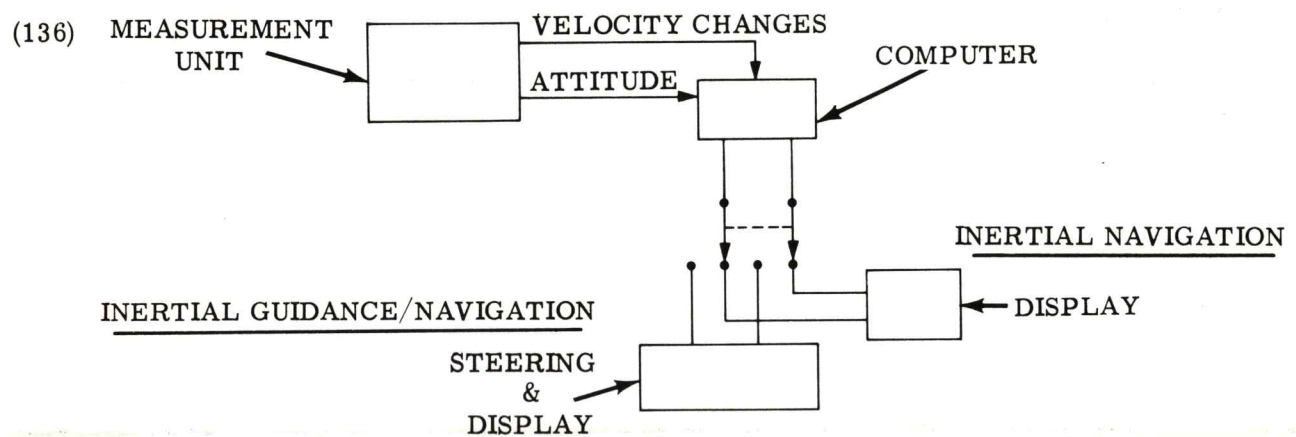
-
- (136) Thus, it is possible to have an inertial navigation system or an inertial guidance navigation system using the same equipment. The defining difference is the computer tasks. To change the task of the computer usually can be accomplished by internal program changes.

-
- (137) A good way to give meaning to these ideas is to remember that:

1. An Inertial Guidance/Navigation System does the complete job of going from one point to another - no pilot or navigator is required.
Examples: Ballistic Missile Weapon System
Aircraft Auto Pilot
2. An Inertial Navigation System only displays positional data to the required pilot or navigator.
Examples: Commercial Aviation
Ships at Sea (submarines)
Interplanetary Space Travel

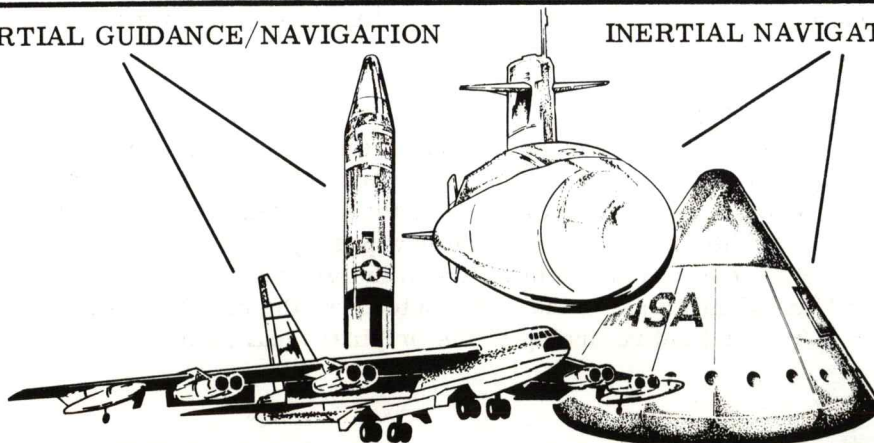
(134)

(135)



(137) INERTIAL GUIDANCE/NAVIGATION

INERTIAL NAVIGATION SYSTEM.



TURN SELECTOR TO POSITION 8

- (138) We will consider our system an Inertial Guidance/Navigation System. Our computer has the capability, as previously mentioned, of steering the vehicle according to some pre-determined flight. No pilot or navigator will be required in our vehicles; however, passengers may well be on board.

There are no restrictions on our Inertial Guidance/Navigation System that would inhibit any type mission.

-
- (139) Since we have built the equipment and understood its basic operation, it might be well to take a look at some of the navigation problems our system might be called upon to solve. We will start by defining the two types of inertial guidance. Remember, we use an Inertial Guidance/Navigation System to find out where we are (navigate) and to do steering (guide).

(140) INERTIAL GUIDANCE TECHNIQUES

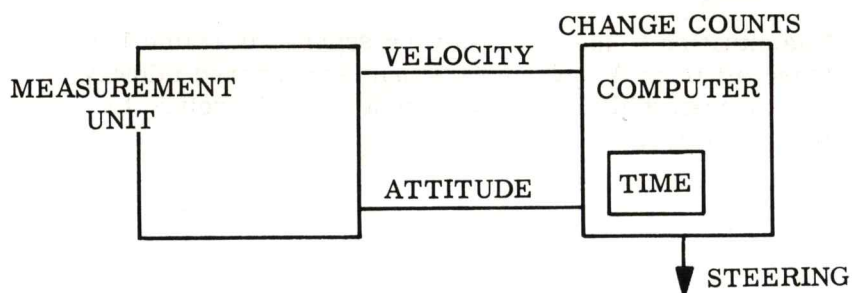
The two methods of Inertial Guidance techniques that are used to guide a vehicle are:

1. IMPLICIT GUIDANCE
2. EXPLICIT GUIDANCE

-
- (141) Implicit Guidance is a method of Inertial Guidance that uses a least distance route to the destination from the present position.

EXAMPLE: It is desired to fly from point A to point B. Midway an unexpected storm was encountered forcing the aircraft to be displaced from the ideal straight line between the two points. The Inertial Guidance/Navigation Computer immediately calculates the new position with respect to the destination and now steers the aircraft to the destination using the best route from the present position rather than returning to the original ideal path.

(138)



(139)

WE KNOW THE EQUIPMENT

NOW

LEARN WHAT IT CAN DO.

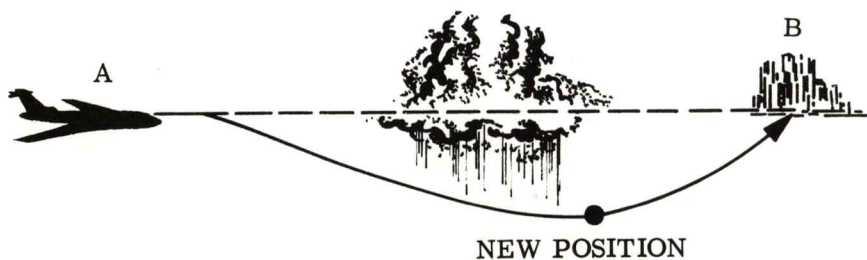
(140)

IMPLICIT - IM-PLISS-IT

EXPLICIT - EX-PLISS-IT

(141)

IMPLICIT GUIDANCE



Implicit guidance techniques continually solve the guidance to destination problem insuring that the _____ route from present position to destination is used.

- A. longest
- B. original
- C. shortest
- D. all of the above.

TURN SELECTOR TO POSITION 9

- (142) Explicit Guidance is the method of Inertial Guidance that guides the vehicle in such a way that it will always follow the "ideal route".

EXAMPLE: The situation is the same as we discussed in frame 141 (Aircraft from A to B with a storm encountered midway). The aircraft will not fly a new route but will return to the "ideal route".

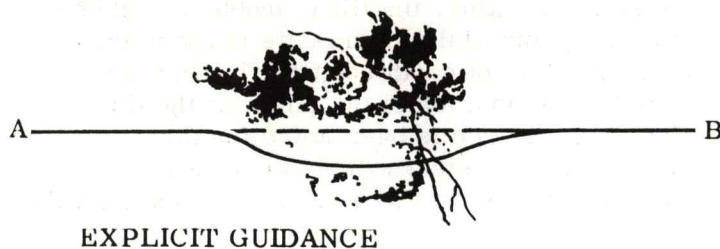
-
- (143) Implicit guidance or explicit guidance can usually be accomplished with the same equipment. The only change necessary is to program the computer to solve the Guidance/Navigation problem in the desired method.

-
- (144) When a specific attitude and velocity are required at the destination, explicit guidance will fulfill the need. The time of travel and total distance will not necessarily be a minimum using explicit guidance techniques.

Implicit guidance is usually used when time of travel and total fuel are constraints on the mission.

-
- (145) Either type of guidance is functional as a method of reaching a destination. The specific parameters concerning the vehicle, power sources, accuracy requirements and arrival restraints will dictate the type of guidance technique best suited for the job to be done.

(142)

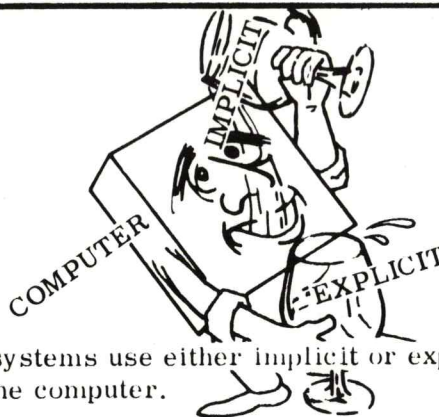


Explicit guidance is the technique of guiding along an ideal route from start point to destination. If the vehicle varies from this course -- it returns to the course.

- A. True
- B. False
- C. ----
- D. ----

(143)

THE COMPUTER IS LOADED WITH INFORMATION THAT WILL SOLVE THE GUIDANCE/NAVIGATION PROBLEM EITHER EXPLICITLY OR IMPLICITLY.



Inertial guidance/navigation systems use either implicit or explicit guidance techniques -- dependent on programing of the computer.

(144)

(145) HOW MUCH FUEL YA GOTTS,
HOW FER IS WE GUNG,
IS THE DESTINATION HOLDN STILL.



SUMMARY:

IMPLICIT GUIDANCE
(Least Distance Route
Continuously Updated)

EXPLICIT GUIDANCE
(Ideal Route)

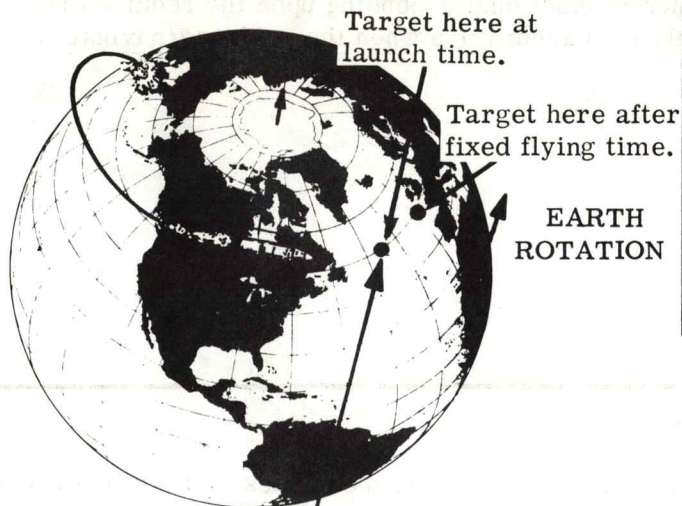
TURN SELECTOR TO POSITION 10

- (146) A good example of implicit guidance is in ballistic weapon systems where a missile (certainly unmanned) is to carry a destructive payload from one point on earth to another point on earth. If the earth were not rotating, the flight problem would be quite simple. However, the earth is rotating and while the missile is flying the earth is rotating underneath it. Knowing the rate of earth rotation (1 revolution each 24 hours) and fixing the time of flight, the position of the target at the time of arrival of the payload is known. Implicit guidance is best suited for this mission because the inertial guidance/navigation system will fly the best route to insure payload delivery at a fixed time. If the missile was late or early on arrival, the target would not be there.

-
- (147) You can probably see that explicit guidance would not be as suited for the Ballistic Weapon System. If we guided the missile back to the ideal flight path each time the missile deviated, it would "waste time" and there would be a good chance for the time of flight to vary sufficiently so that it would be impossible to hit the target.

-
- (148) Explicit guidance has applications in orbital injections where it is desired to place a payload in a specific orbit around the earth. It is imperative that a specific attitude and velocity is achieved at a specific point in space - the time it takes to reach the destination is not always of paramount importance. (Note: Implicit Guidance could also be used for this type mission where time of flight is important.)

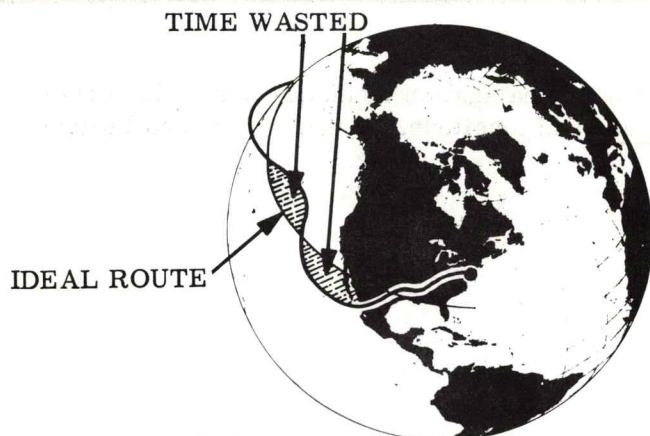
(146)



Time is quite important in a ballistic missile flight because the missile must reach a destination point at the same time the target does. This condition is due to:

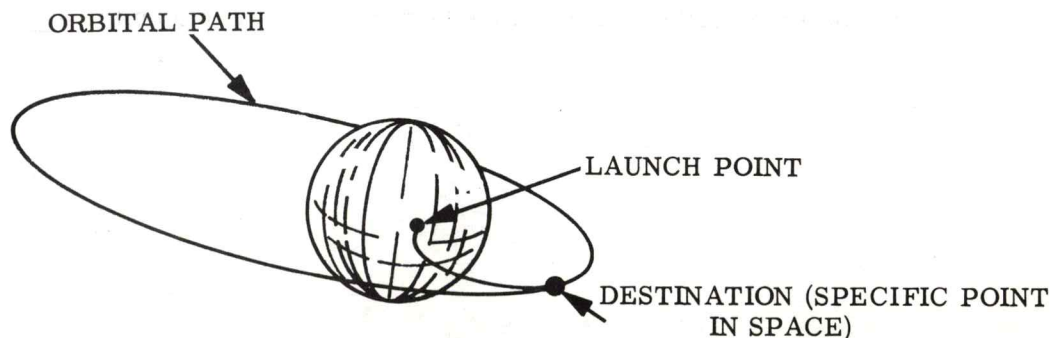
- A. moon-earth relations.
- B. explicit guidance.
- C. earth rotation.
- D. none of the above.

(147)



NOTE: In the illustration shown, if implicit guidance were being used the guidance system would direct the missile to take the shortest path to the target. If the missile varied off path, then a new path is determined from its present position to target, not back to the ideal route from start point to target.

(148)



EXPLICIT MIGHT BE USED WHERE WE ARE MOST INTERESTED IN ACHIEVING AN EXACT ORBIT.

TURN SELECTOR TO POSITION 11

- (149) Keep in mind that space travel does not necessarily imply implicit guidance techniques. Either type of inertial guidance is functional depending upon the required results. Both techniques result in extremely high accuracies when the guidance/navigation equipment is of a high quality.

(150) GUIDANCE/NAVIGATION PROBLEMS

Now that we have discussed two types of guidance techniques, let's talk about some common guidance/navigation problems. We will discuss basic earth navigation and basic orbital theory. We will keep the mathematics to a minimum, using only that which is necessary for basic understanding of the subject matter.

(151) EARTH BOUND NAVIGATION

In order for us to understand any earth bound navigation techniques, it is important that we understand the meaning of latitude and longitude. If you understand latitude and longitude, proceed to frame 161.

-
- (152) If the earth could be cut in half at the equator, the upper section shown would constitute the northern half and the bottom section would be the southern half.

(149)

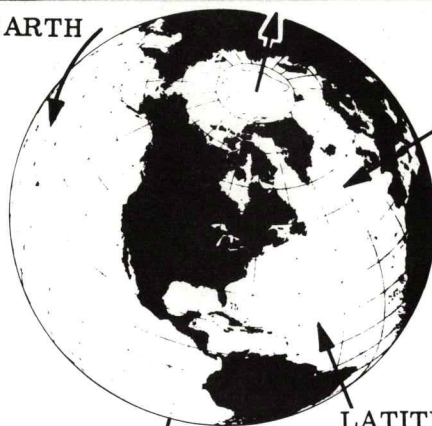
WITH GOOD GUIDANCE/NAVIGATION EQUIPMENT EITHER GUIDANCE
TECHNIQUE IS VERY ACCURATE AND RELIABLE.

(150) LET'S DISCUSS SOME BASIC EARTH AND SPACE NAVIGATION PROBLEMS.



(151)

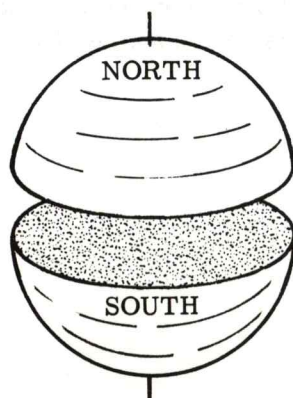
EARTH



LINES OF LONGITUDE

LATITUDES

(152)



PRETTY LOGICAL, HUH!

TURN SELECTOR TO POSITION 1

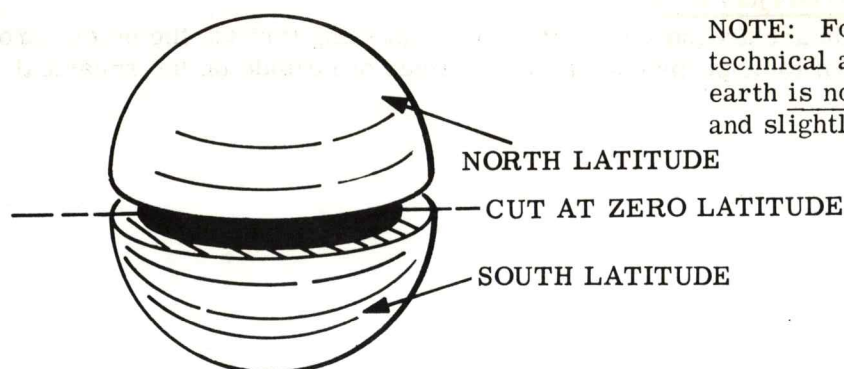
- (153) Lines of latitude are imaginary lines going around the earth parallel to the equator. The equator is considered zero latitude. All lines that are scribed in the top section are considered North latitude lines and all lines parallel to the equator in the bottom half are South latitude lines.

-
- (154) The identification of the latitude lines is by first identifying either the north or south section, then by stating the number of degrees up or down from the equator the line is located. (The north pole is 90° north latitude, the south pole is 90° south latitude.)

-
- (155) There could be an infinite number of latitude lines on charts and maps of the earth but for practical applications the lines of latitude are drawn at the most convenient scale for a particular chart or map.

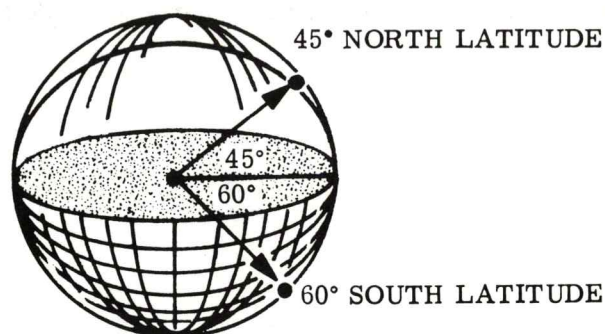
-
- (156) If the earth is cut by a plane passing through the north and south poles, then the intersection of the surface of the earth and the plane is called a line of longitude.

(153)



NOTE: For you sticklers on technical accuracy. . . . the earth is not actually cut in half and slightly separated.

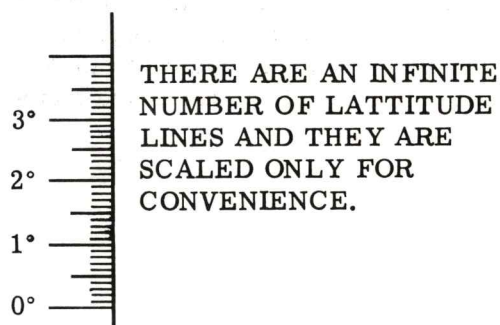
(154)



Latitude lines located above the equator are referred to as:

- A. north latitude lines.
- B. 60° down latitude.
- C. 45° latitude lines.
- D. the north pole.

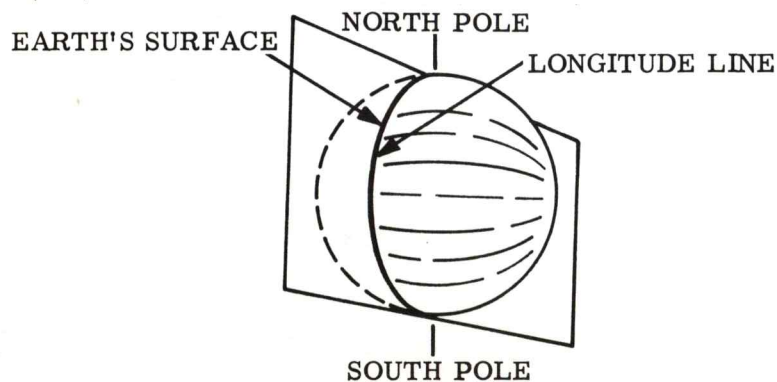
(155)



Lines of latitude are parallel to the:

- A. earth's north-south axis.
- B. 45° east latitude.
- C. earth's equator.
- D. earth's spin axis.

(156)



The intersection of a plane passing through the north and south poles of the earth and the surface of the earth would form a line called a line of:

- A. equator.
- B. longitude.
- C. latitude.
- D. intersection.

TURN SELECTOR TO POSITION 2

(157) Lines of longitude are around the earth, always passing through the poles. You can consider them to be perpendicular to the lines of latitude on the spherical surface.

(158) Longitude lines indicate your position around the earth. In order for these lines to have meaning, however, we need some reference or a zero longitude line.

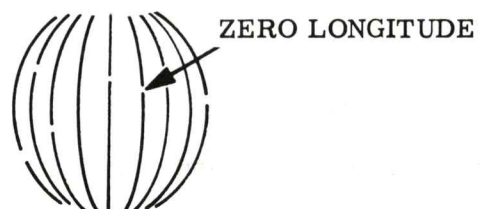
(159) Zero longitude is defined by the longitude line which passes through Greenwich, England. Longitudes east from zero longitude are east longitudes and those west from Greenwich are west longitudes, and are indicated in degrees from Greenwich. The longitude lines are illustrated on charts and maps to a scale convenient for easy interpretation.

(160) Any point on earth can be defined by use of latitude and longitude. This then is really an earth positional coordinate system.

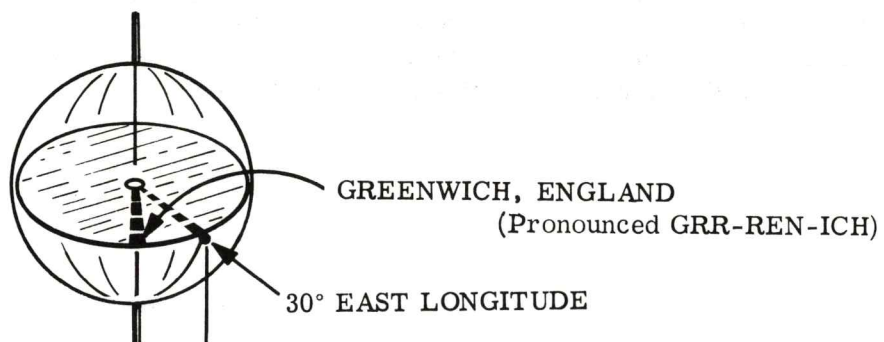
- (157) Lines of longitude perpendicular to the latitude lines



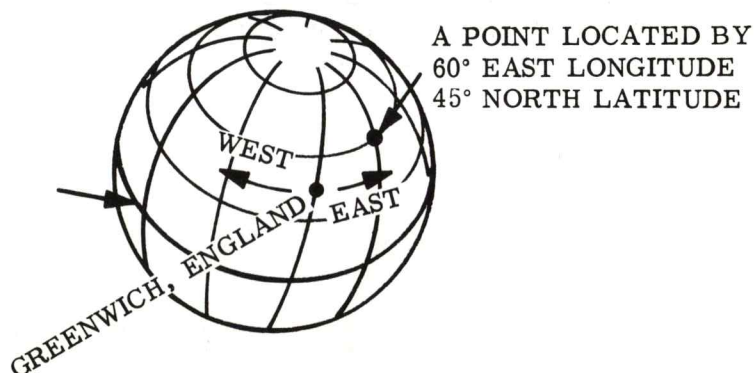
- (158)



- (159)



- (160)



TURN SELECTOR TO POSITION 3

(161) Lines of latitude and longitude are the basis for earth navigation systems. If you know your latitude and longitude then you know your position. There are two basic methods of proceeding from one position to another position on earth. (We will neglect highway travel and consider air travel or sea travel.)

(162) The two methods, or routes, between two points on earth are:

1. Rhumb line route
2. Great circle route

Both are defined in terms of latitude and longitude.

(163) A great circle route connecting two points on earth is defined as the line of intersection of the earth with a plane which contains the center of the earth, the start point, and the destination. (By this definition, all lines of longitude are great circle routes for north-south travel, aren't they?)

YES!

(164) A great circle route is the shortest distance between two points on earth. Long sea voyages or long air trips usually follow great circle routes because it is the shortest and most efficient way.

(161)

HIGHWAY TRAVEL IS "PEOPLE TRAVEL" AND DOESN'T HAVE ANY NECESSARY APPLICATIONS IN INERTIAL GUIDANCE/NAVIGATION SYSTEMS.

(162)

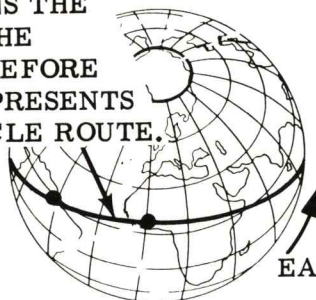
RHUMB LINE

GREAT CIRCLE

The two techniques we shall observe which apply to earth navigation are called great circle and _____ line.

- A. longitude
- B. rhumb
- C. latitude
- D. equatoreal

(163) THE PLANE OF THIS LINE CONTAINS THE CENTER OF THE EARTH, THEREFORE THE LINE REPRESENTS A GREAT CIRCLE ROUTE.



EARTH ROTATION

A plane defined by earth center, start point and destination, when intersecting the earth's surface forms a/an:

- A. none of these answers are correct.
- B. equatorial line.
- C. latitude 45° north.
- D. great circle.

(164)

GREAT CIRCLE ROUTES ARE:

1. THE SHORTEST DISTANCE BETWEEN TWO POINTS
2. MOST EFFICIENT ROUTES.



THIS IS IMPORTANT. . .

ESPECIALLY when short on fuel!!!!

TURN SELECTOR TO POSITION 4

- (165) Rhumb line routes are routes which are a straight line between two points on earth. Even though it would appear that the rhumb line route is the shortest distance between two points, it is not. Proof of this lies in spherical geometry (which we won't cover in this text). It is sufficient to say that on a flat surface the shortest distance between two points is a straight line, on a spherical surface a great circle route is the shortest distance.

-
- (166) Why does anyone ever choose the rhumb line route if its further? The main reason rhumb line routes are used is because they are easier to follow. The heading from start to finish is the same. So for relatively short distances (a few hundred miles) the rhumb line route isn't much further than the great circle route and it is easier to follow.

-
- (167) Great circle navigation/guidance is truly the shortest distance but is harder to navigate because the vehicle heading is constantly changing to form what appears as an arc on a section of the earth.

It is not expected that you will have a very complete understanding of the details of rhumb line and great circle navigation from this description. The reason that they are mentioned is that you ought to know that they exist. For now, if you know the two basic routes and the primary advantage and disadvantage of each, this is sufficient.

-
- (168) Our inertial guidance/navigation system is capable of controlling a vehicle along either one of these routes. The routing is placed in the computers memory and on the basis of continual comparison of present position and destination, appropriate steering will result. We will now discuss the method of accomplishing this result.

(165)

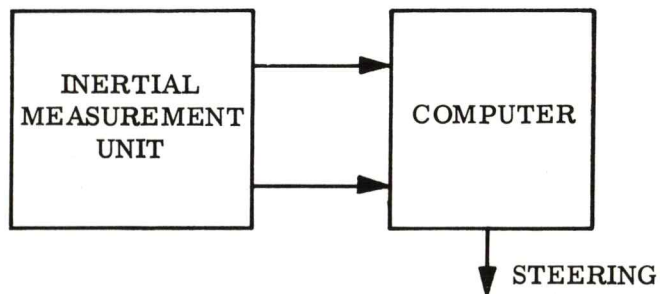
(166)

THE HEADING FOR A
RHUMB LINE ROUTE IS
CONSTANT, BUT THE
DISTANCE TRAVELED
IS FURTHER.

(167)

THE HEADING FOR A
GREAT CIRCLE ROUTE
IS CONSTANTLY
CHANGING, BUT THE
DISTANCE TRAVELED
IS SHORTER.

(168) OUR GUIDANCE COMPUTER MAY USE EITHER GREAT CIRCLE OR RHUMB LINE
NAVIGATION TECHNIQUES.



We have learned that there are two types of inertial guidance techniques implicit and explicit.

1. Implicit Guidance refers to the guidance technique where the vehicle is steered to the destination via the best route from its present position.
2. Explicit Guidance refers to the guidance technique where the vehicle is steered to the destination via the "ideal flight path". Any deviations the vehicle makes from the "ideal flight path" are immediately corrected.
3. We defined latitude and longitude as the earth's coordinate system with zero degrees latitude being at the equator and zero degrees longitude located at Greenwich, England.
4. We discussed the two types of earth navigation most commonly used - rhumb line and great circle. We found that a great circle route is the shortest route between two points on earth but the rhumb line might be considered easier to use in terms of headings.

(169) SPACE FOR NOTES:

TURN SELECTOR TO POSITION 6

(170) TYPICAL EARTH REFERENCED FLIGHT USING INERTIAL GUIDANCE/NAVIGATION

The system has been built, the review of earth navigation has been accomplished and it would appear that we are ready to use our knowledge to go on a trip, so. . . . let's do it. We will go from Milwaukee to Des Moines in our aircraft which is equipped with an inertial guidance/navigation system. We will follow a rhumb line route. Since the pilot will do the steering no commands will be required from the computer.

(171) What information must our system have prior to departure? As previously mentioned, it needs to know:

1. Exactly where it started
2. Exactly where it must go.

We are not concerned with the time of flight because we have plenty of fuel and, just as important, the destination is not moving with respect to the start point.

(172) Let's take a closer look at the requirements prior to departure. The start point is Milwaukee and is located at 43° north latitude and 88° west longitude (this identifies where, on earth, Milwaukee is located).

(173) PLATFORM ERECTION

The identification of the latitude and longitude of Milwaukee is part of the pre-departure information required, but it is not sufficient information for our inertial guidance/navigation system. The system must be "erected" so that we know its orientation in Milwaukee.

"Erected" is when the stable member is stabilized and the acceleration sensitive axes of the accelerometers are in a known orientation.

(170)



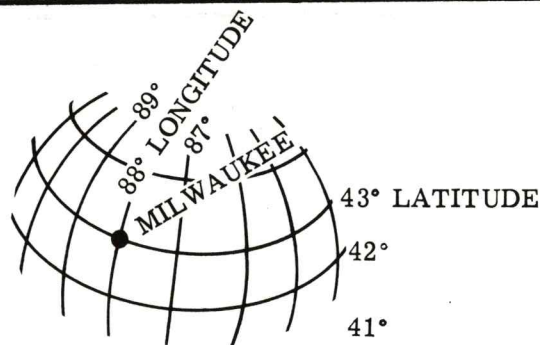
(171) MUST KNOW:

1. START POINT
 2. DESTINATION POINT
- TIME (DON'T CARE)

Our inertial navigation system must know:

- A. exact start point.
- B. exact destination point.
- C. time of start.
- D. A and B are correct.

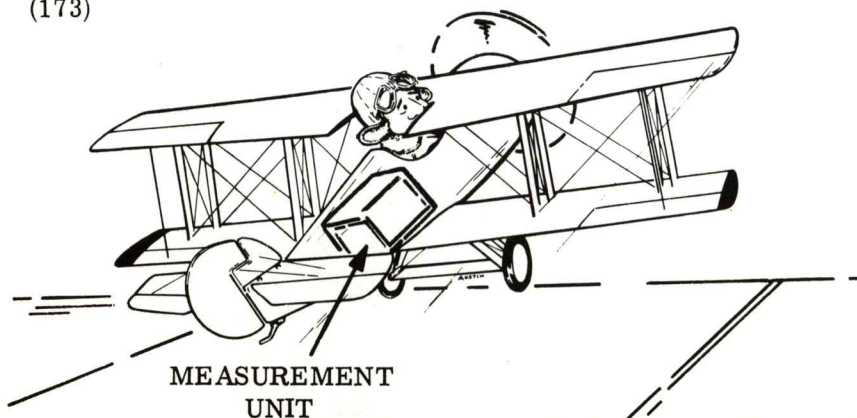
(172)



A specific latitude and longitude will identify the exact location of a particular destination.

- A. True
- B. False
- C. ----
- D. ----

(173)



A new term, guidance system "ERECTION" means that the stable member is stabilized and the accelerometer orientations are:

- A. straight north.
- B. at random.
- C. known.
- D. parallel to the equator.

TURN SELECTOR TO POSITION 7

(174) You recall that our three accelerometers were placed on the stable member so that they always pointed in the same direction, regardless of what the vehicle did. If the airplane violates the law and does aerobatics while enroute, it won't effect the inertial guidance/navigation system.

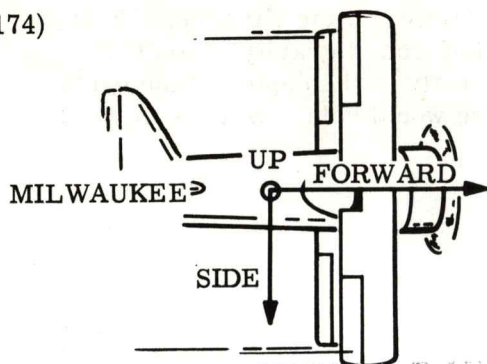
(175) In order to "erect" our system we will do two things:

1. Point the accelerometers in a known direction,
2. Tell the computer how the axes are aligned so it will have a reference.

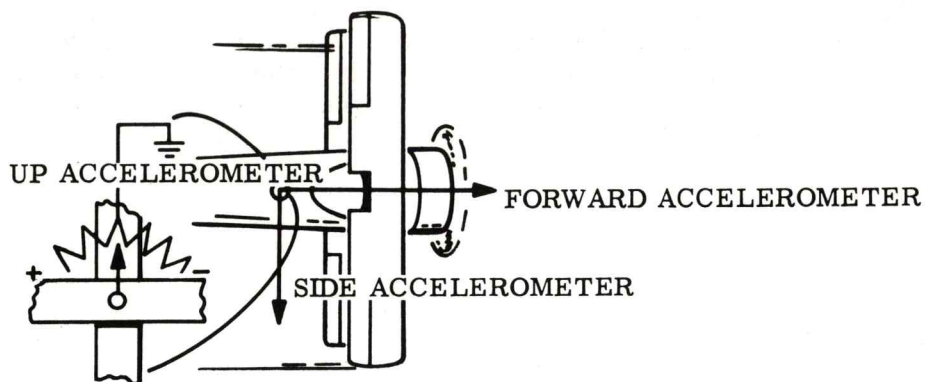
(176) We taxi the aircraft out of the ramp area and go over to an area that allows us to position the aircraft in a specific attitude. The erection procedure will be accomplished in this area. The pilot presses the button that says "**GUIDANCE ERECT**". What happens? Let's find out.

(177) The inertial guidance/navigation system will sequentially, one step at a time, orient the accelerometers to a known specific position. . . . let's see how.

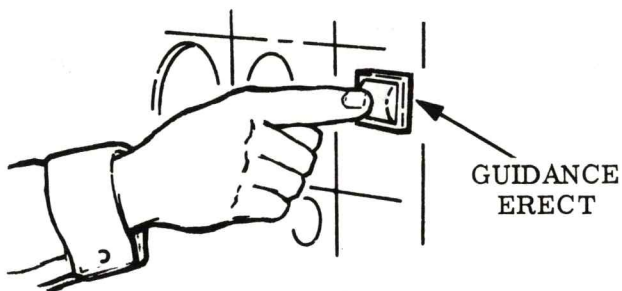
(174)



(175)



(176)



(177)

- STEP 1 - ALIGN UP ACCELEROMETER
- STEP 2 - ALIGN SIDE ACCELEROMETER
- STEP 3 - CHECK ALIGNMENT
- ETC.

TURN SELECTOR TO POSITION 8

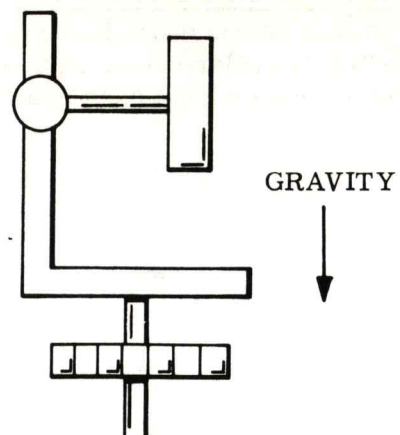
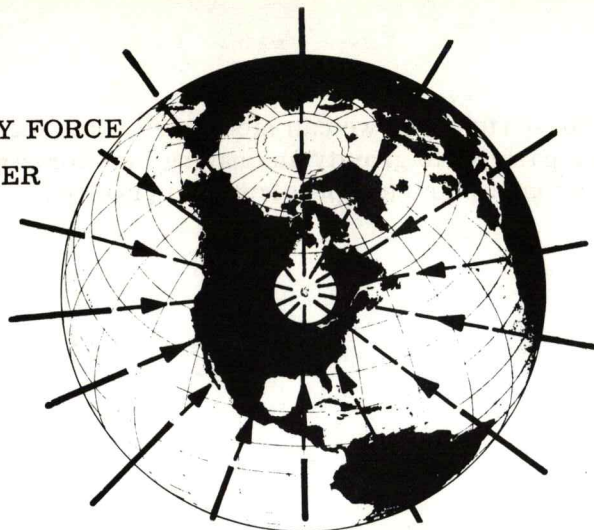
(178) One very good reference for the UP accelerometer is gravity. If the UP accelerometer input axis is properly positioned it will be parallel to the force of gravity - won't it? Practically speaking, the force due to gravity points directly to the center of the earth. If we can use this fact to erect the stable member it sure would help. Well -- we can!

(179) Recall the accelerometer construction and action. When the spinning wheel tried to drop, the entire "L" shaped bracket rotated. The rate of rotation of the "L" bracket identified the magnitude of the force on the displaced wheel. When the spin axis of the wheel is perpendicular to the acceleration, then the maximum force will be exerted on the pendulus wheel assembly, thus, the greatest turning rate of the "L" shaped bracket.

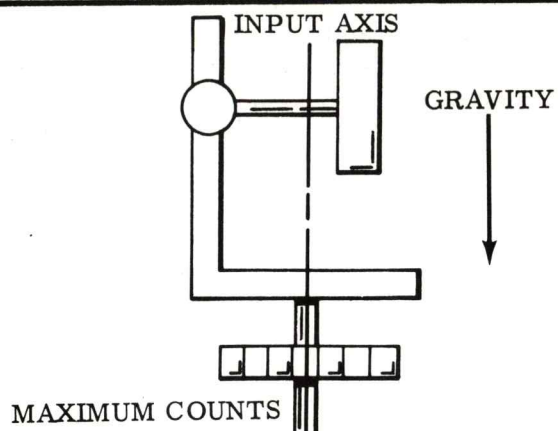
(180) Assume gravity in the direction shown. Further assume the wheel and arm to be equally functional regardless of its orientation. (It will work on its side, upside down or any orientation.) Now - if the accelerometer is placed so that its input axis is parallel to gravity, then a maximum counter reading will be displayed (8 counts per second - refer to frame 115 for a review). If the input axis of the accelerometer is horizontal then a minimum number of counts are displayed, in fact - zero.

(181) The intermediate positions that the accelerometer is in (as it goes from vertical to horizontal) result in counter readings which are proportional to the angle that the input axis makes with the force of gravity. (Number of counts = $8 (\cos \Theta)$ if you are using a perfect accelerometer).

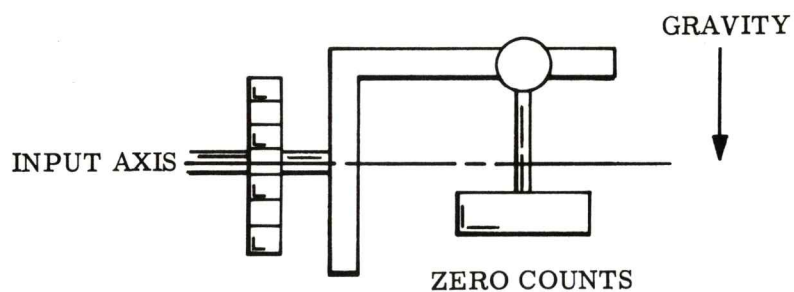
(178) GRAVITY FORCE
TOWARD CENTER
OF EARTH



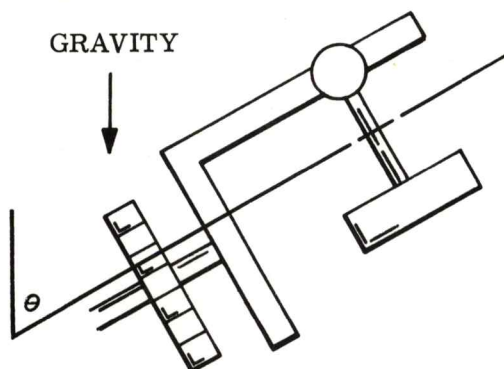
(179)



(180)



(181)



TURN SELECTOR TO POSITION 9

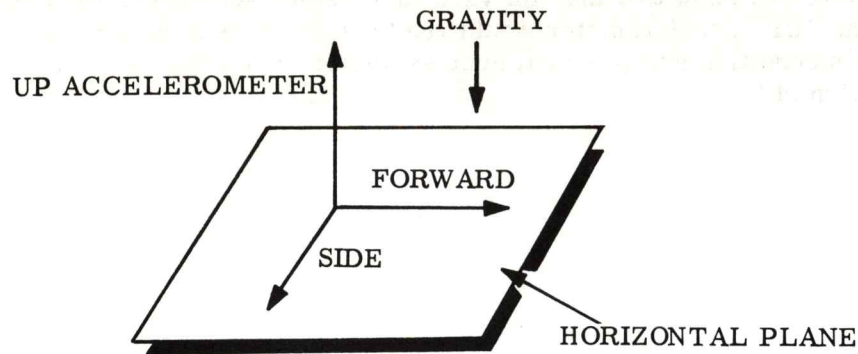
- (182) With this information, it sounds reasonable that we can mechanize some way of aligning the "UP" accelerometer input axis parallel to gravity and having the "forward" and "side" accelerometer input axes in a horizontal plane (perpendicular to gravity).

-
- (183) We will use the fact that two lines define a plane. If, again assuming that the accelerometers are mounted on the stable member orthogonally, the side and forward accelerometers both sense zero gravity they will define the horizontal plane and, in so doing, will position the "UP" accelerometer input axis parallel to gravity.

-
- (184) We will do exactly this. The computer will monitor the counts received from each accelerometer. It will, on the basis of these counts, send a signal back to the measurement unit that will force motors, mounted on the gimbals, to position the stable member so that the forward and side accelerometers are correctly positioned in the horizontal plane. (Keep in mind that gyros haven't been started or used.)

-
- (185) If the rate of counts is increasing then the accelerometer input axis is getting closer to being parallel with gravity. Conversely, if the accelerometer counts are decreasing in rate the accelerometer is getting closer to being horizontal. On the basis of count rate, the computer determines which way the stable member must be moved in order for a particular accelerometer to meet its intended requirements (either a zero count or maximum count).

(182)

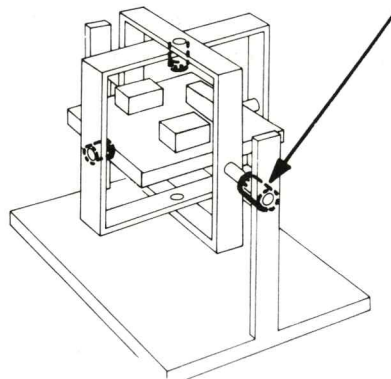


(183)

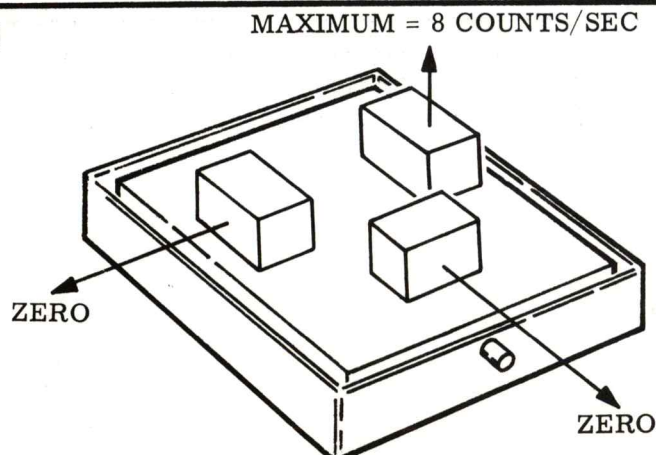
When the forward and side accelerometers sense zero gravity, we can assume the vertical or UP accelerometer is:

- A. sensing zero gravity also.
- B. sensing .707 g's.
- C. senses a portion of 1 g.
- D. senses 1 g.

(184) MOTORS MOUNTED ON GIMBAL AXIS FOR POSITIONING THE STABLE MEMBER.



(185)



When a particular accelerometer is producing zero counts, we know that its positive input axis is positioned in the horizontal.

- A. True
- B. False
- C. ---
- D. ---

TURN SELECTOR TO POSITION 10

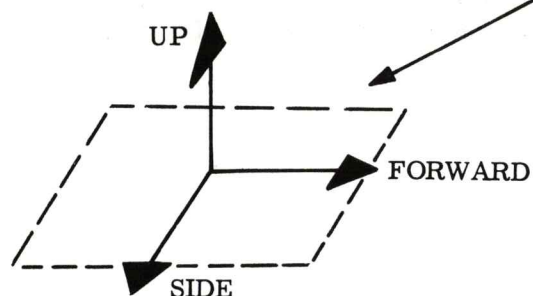
(186) A second look will show that the "forward" and "side" accelerometers must read zero and the "UP" accelerometer would read maximum if it were monitored. Let's say that this condition exists - what accelerometer or accelerometers do we know the exact position of?

(187) You are right. Only the "UP" accelerometer. The forward and side accelerometers are in a horizontal plane but we don't know where they are in this plane. Our next step in erecting the stable member will be to position the forward and side accelerometers to a specific direction (azimuth alignment).

(188) There are many methods of doing this, "Azimuth alignment". Electro-optical methods, gyro compassing methods and many others. In this portion of the text we will use gyro compassing to achieve our goal of positioning the accelerometers in the horizontal plane.

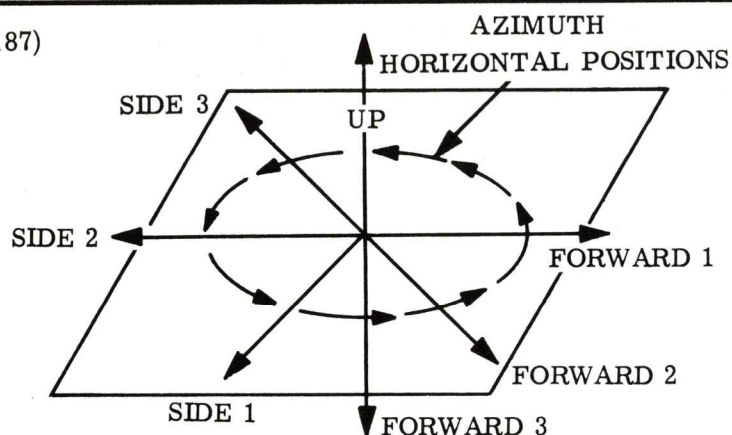
(189) To understand gyro compassing, we will again depend upon your recall of basic gyro theory. NOT ACCELEROMETERS. (Review frames 35 through 55 if the illustration on the right doesn't ring any bells.) Now! Turn on the gyros and get their wheels spinning.

(186)



ZERO COUNTS FROM SIDE AND FORWARD
ACCELEROMETERS INDICATE THEY HAVE
BEEN POSITIONED INTO THE HORIZONTAL.

(187)

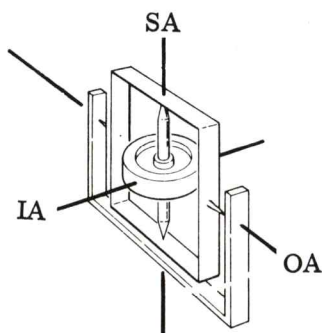


NOTE: Although the forward and side accelerometers are orthogonal and are in the horizontal when zero counts are produced, we are still not sure in what direction these two accelerometer axes are pointing. When we do position these accelerometers (about the UP axis) in the horizontal plane -- we say that they are being positioned in azimuth.

(188)

THE TECHNIQUE OF INSURING A KNOWN DIRECTIONAL POSITION OF THE
ACCELEROMETERS THAT WE SHALL VIEW IS CALLED GYRO COMPASSING.

(189)



TURN THEM ON

TURN SELECTOR TO POSITION 11

(190) It's time for an earth moving announcement!!

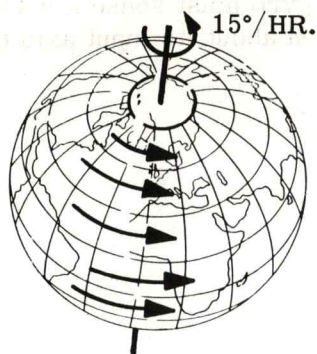
The earth is rotating at a rate of approximately 15° per hour, now isn't that something? Well, we are going to use this fact to obtain azimuth information for erection.

(191) If you were a gyro and you were sitting on the earth, you could feel some rotation about your input axis. Assume you, as a gyro, are sitting on the north pole. Your positive input axis is pointing straight up.

(192) Looking from outer space, you, sitting on the north pole, are spinning at 15° per hour. If the input axis is along the spin axis of the earth there is a rotation rate about the gyros input axis of 15° /hour. We know that if the input axis of a gyro is rotated the gyro will precess causing a rotation about the output axis. With our monitoring device, assuming we started at a null, we could read a value of voltage which indicates magnitude of rotation and direction of rotation by the voltage polarity.

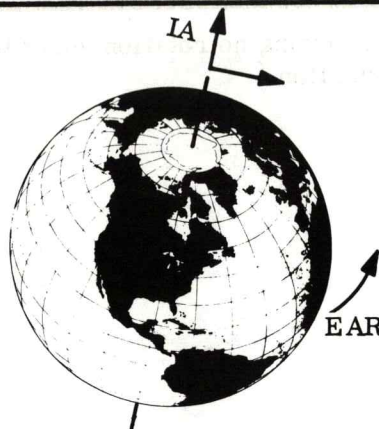
(193) Now, still at the north pole, rotate the gyro so that its input axis is pointing perpendicular to the spin axis of the earth. . . . what happens?

(190)



WE MUST SEE HOW THE ROTATION OF
THE EARTH EFFECTS ERECTION OF OUR
GUIDANCE SYSTEM.

(191)



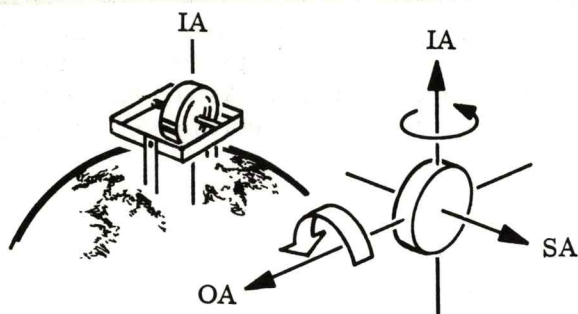
EARTH ROTATION IS OFTEN SHOWN AS
 ω_E .

The symbol ω (Omega) is used to
represent angular velocity and the
subscript "E" indicates Earth.

ω_E = Angular Velocity of the Earth.

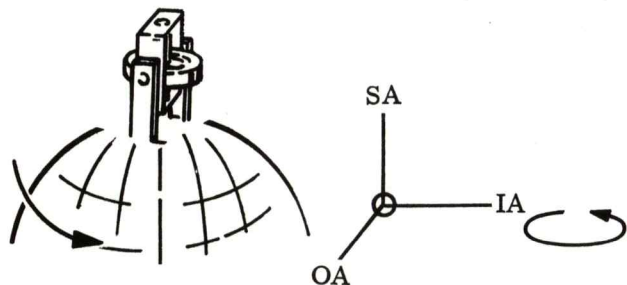
EARTH ROTATION (ω_E)

(192)



IF THE GYRO IS POSITIONED
AS SHOWN. . . NOTICE FULL
EARTH ROTATION IS FELT
ABOUT IA.

(193)



NOTICE. . . .the rotational input is
parallel to the input axis.

TURN SELECTOR TO POSITION 1

- (194) Right -- the gyro does not feel a thing. Don't forget, a gyro must sense a rotation about its input axis. In this position it won't have a net rotation about its input axis thus no reason to precess.

-
- (195) This concept of no rotation about the input axis producing no rotation about the output axis is very fundamental to inertial guidance/navigation.

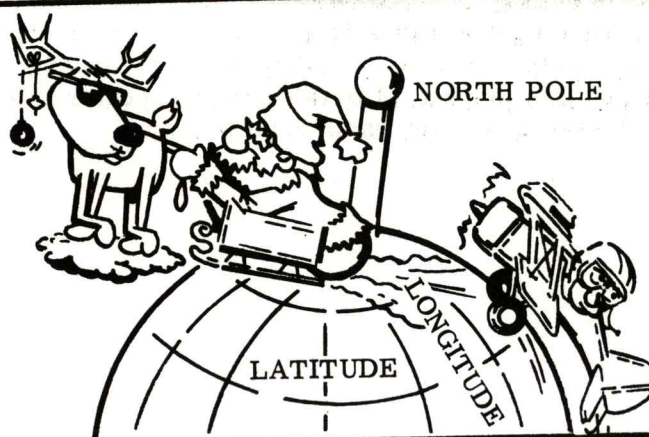
-
- (196) Now let's use these gyro characteristics to align the stable member in azimuth. Obviously we can't go to the north pole every time we want to erect the stable member (could have trouble bumping into reindeer, too!). As you have probably guessed, anything we said about the gyros behavior at the north pole is true anywhere on earth.

-
- (197) We call the $15^\circ/\text{hour}$ that the earth is rotating - 1 earth rate unit (ERU). If a gyro senses 1 ERU this means that it is feeling the full rotation of earth about its input axis. To do this, the input axis of the gyro must be parallel to the spin axis of the earth.

(194)

(195)

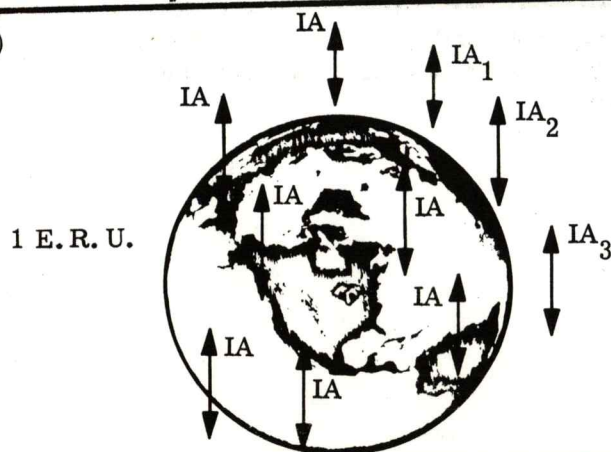
(196)



The effects of earth rotation on a gyro are essentially the same regardless of geographical location.

- A. ----
- B. ----
- C. True
- D. False

(197)



One earth rate unit (E. R. U.) is equal to _____ degrees per hour.

- A. 5
- B. 15
- C. 50
- D. 360

TURN SELECTOR TO POSITION 2

- (198) If the input axis of the gyro is perpendicular to the spin axis of the earth, then zero ERU is felt. . . . thus no precession.

-
- (199) It sounds reasonable then if the input axis of the gyro is between being parallel and perpendicular to the spin axis of the earth then a portion of earth rate will be felt by the gyro. (1 ERU (sine λ) for those of you interested.)

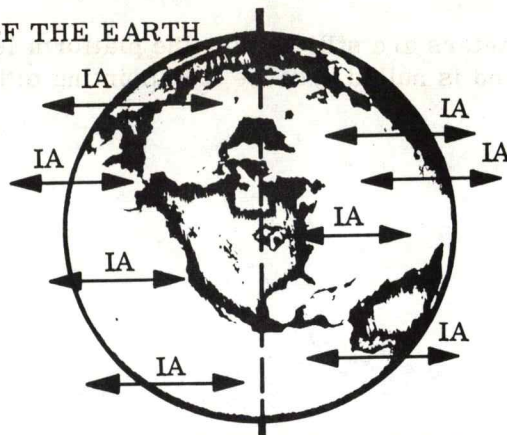
λ is the Greek letter lambda which represents latitude.

-
- (200) Here we are sitting in Milwaukee, what good will this "gyro stuff" do? Well, the gyros work as well in Milwaukee as they do at the north pole, so let's use them. If we use gyro 3 (whose input axis is parallel to the forward accelerometer input axis) and orient it so that it doesn't sense any earth rotation, what direction is it pointing?

-
- (201) Right! Either straight east or straight west, not north or south. For the gyro to feel any earth rotation it would have to be pointed away from a given line of equal longitude (not parallel to the equator).

(198) SPIN AXIS OF THE EARTH

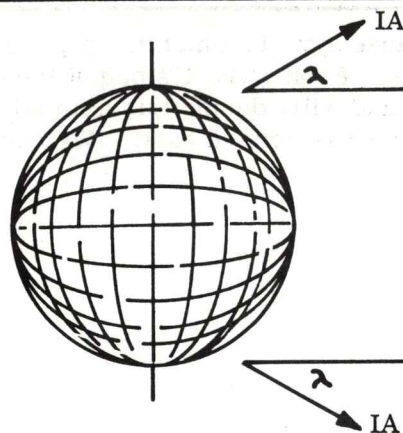
ZERO E. R. U.



With the input axis parallel to the earth spin axis, the gyro senses full earth rate. With the input axis perpendicular to earth rate, the gyro senses zero earth rate.

- A. False
- B. True
- C. ----
- D. ----

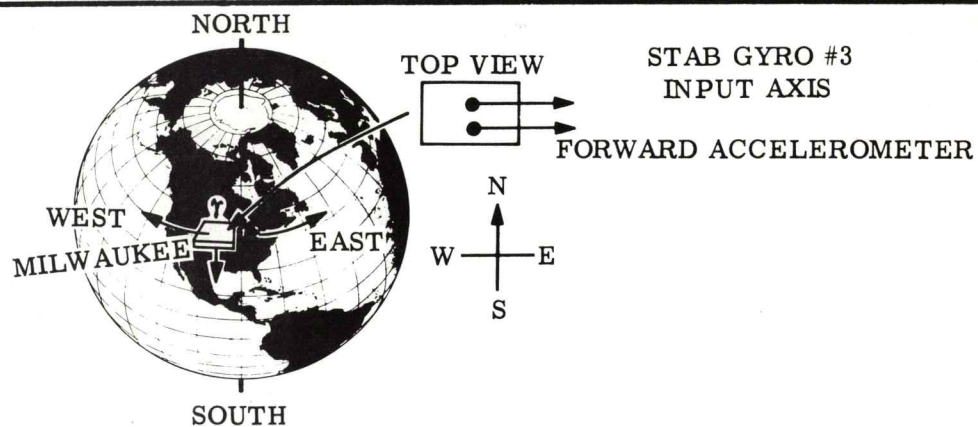
(199)



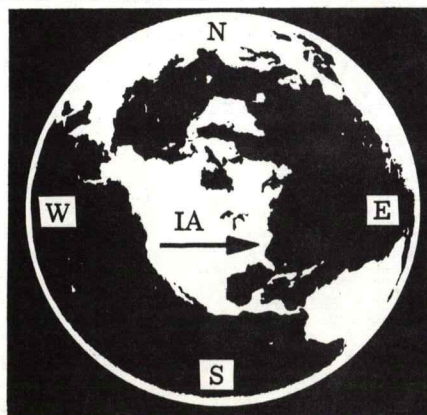
If the IA is at some angle between being parallel or perpendicular to the earth spin axis then the gyro senses:

- A. zero earth rate.
- B. full earth rate.
- C. a portion of full earth rate.
- D. none of the above.

(200)



(201)

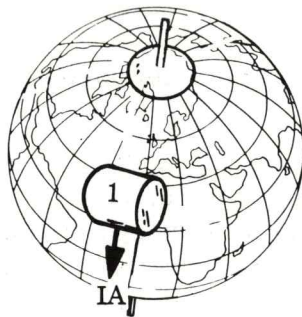


TURN SELECTOR TO POSITION 3

- (202) Keep in mind that the accelerometers are still holding the platform level so that gyro 3 is in a horizontal plane and is nulled because it is pointing either east or west.

-
- (203) We know that gyro 3 is pointing east because gyro 1, which is perpendicular to it, is sensing a portion of the full earth rotation. From gyro 1's output the direction of rotation about its input axis is measured and will, during this azimuth erection, be monitored electrically so as to insure gyro 3 is pointed east. (We could have chosen west if we so desired.)

(202)



THE INPUT AXIS OF GYRO
NUMBER ONE IS NOT
POINTED EAST OR WEST
AND IS THEREFORE
SENSING A PORTION OF
EARTH RATE.

Assuming the three gyro input
axes are mutually perpendicular,
what value of earth rate will gyro
2 be sensing?

- A. 1 E. R. U.
- B. 0 E. R. U.
- C. 2 E. R. U.
- D. a portion of 1 E. R. U.

TURN SELECTOR TO POSITION 4

(204) REVIEW OF PLATFORM ERECTION

We have made some pretty big strides in the last few frames. In no sense of the word are we trying to give you the complete mechanization of how erection is accomplished.

The idea of this entire section is to familiarize you with one method of erecting a stable member to an exact known position.

In essence, what we have done is this:

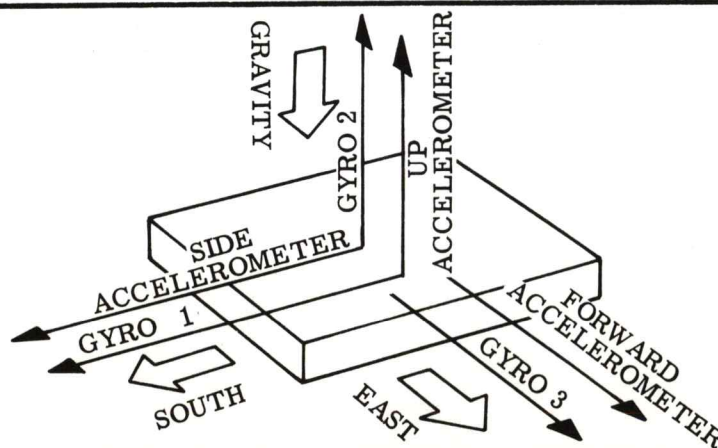
1. Identified geographical location by stating its latitude and longitude.
2. We have given this latitude and longitude information to the computer.
3. We taxied to an area that would position the aircraft, by markings, to a precision heading.
4. We used the association of gravity and accelerometers to establish a horizontal plane.
5. We used earth rotation acting upon our gyros to establish an azimuth reading for our accelerometer. We could do this because the "forward" accelerometer input axis is parallel to the "gyro 3" input axis (likewise "gyro 1" and "side" accelerometer input axis are parallel. "Gyro 2" and "up" accelerometer axis are also parallel).
6. Once the stable member is properly erected, further torquing resulting from earth rate about south gyro will be compensated for.
7. Now the stable member is exactly oriented in Milwaukee.

(205) AN EARTH REFERENCED FLIGHT

For simplicity, let's assume the aircraft was headed due east so that the forward accelerometers positive input axis is pointing right out the front of the aircraft, and the side accelerometer input axis is pointing parallel to the wing center line. (If it were not this way the computer would be informed of the angular deviation between due east and the aircraft's true heading.)

(204) SPACE FOR NOTES:

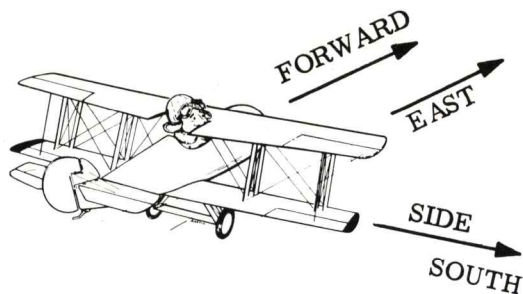
(205)



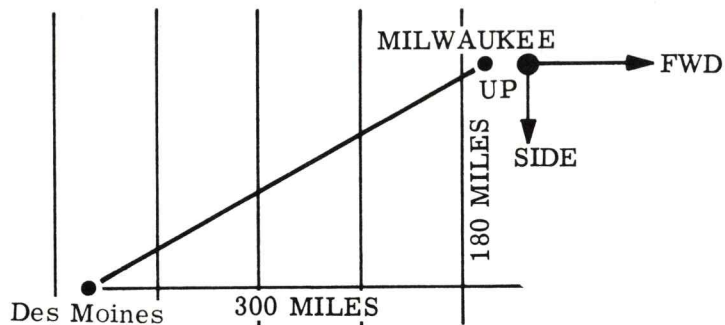
TURN SELECTOR TO POSITION 5

- (206) The system is erected with the accelerometers pointed in a known direction. The gyros are now providing the stability required for the accelerometer reference. No matter what the aircraft does, the forward accelerometer will always point east, the side accelerometer will always point south, and the up accelerometer will always point up (parallel to gravity). Our destination is Des Moines, so let's taxi to the runway for take-off.
-
- (207) We have given the coordinates of Des Moines to the computer. They are $93^{\circ}41'$ west longitude and $41^{\circ}32'$ north latitude. On the basis of this information compared with the latitude and longitude of Milwaukee, the computer calculates the distance in the side direction and the "minus forward" direction (reverse). Recall the forward accelerometer positive input axis is pointing east - thus to fly west results in decrementing the forward accelerometer counter. The distances are 300 miles west and 180 miles south. If the plane travels these distances in the corresponding directions, then it will arrive precisely at Des Moines.
-
- (208) As the aircraft accelerates down the runway in a westerly direction, the forward accelerometer senses the acceleration. The accelerometer wheel tries to fall back as shown in the illustration. Instead, we know that the "L" shaped bracket will rotate in such a direction so as to decrement the counter. Each count received by the computer is then properly scaled to convert the counts to an indication of velocity.
-
- (209) Let's say that as a result of take-off and climbing to altitude, the computer received -55 counts from the forward accelerometer and 33 counts from the side accelerometer. The velocity scale factor is, as previously established, 4 ft/sec/count. This means that the aircraft is now flying at $55 \times 4 = 220$ ft/sec = 150 mi/hr in a westerly direction and $33 \times 4 = 132$ ft/sec = 90 mi/hr in a southerly direction.
-

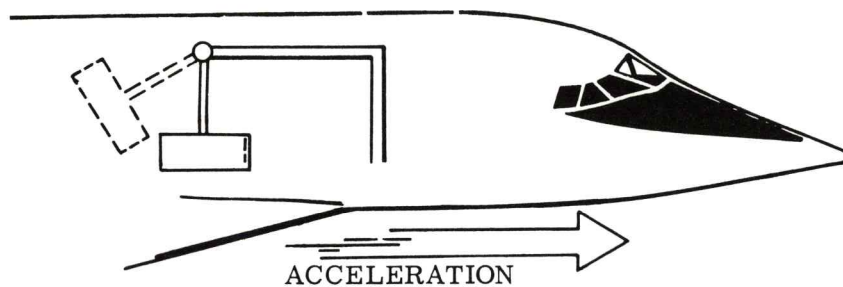
(206)



(207)



(208)



(209)

$$55 \text{ Counts} \times \frac{4 \text{ ft/sec}}{\text{count}} = 220 \text{ ft/sec} = 150 \text{ mi/hr.}$$

$$33 \text{ counts} \times \frac{4 \text{ ft/sec}}{\text{count}} = 132 \text{ ft/sec} = 90 \text{ mi/hr}$$

TURN SELECTOR TO POSITION 6

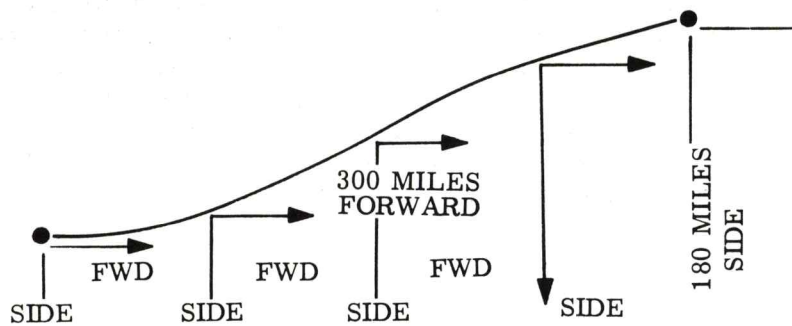
- (210) If no other velocity changes are detected by the forward and side accelerometers, then in about two hours the aircraft will be the required westerly distance of 300 miles and the required southerly distance of 180 miles.

-
- (211) Since Des Moines is south of Milwaukee, the pilot pointed the plane in a south-westerly direction immediately after take-off and this accounted for the accumulation of counts on the side accelerometer. The actual forward velocity (in a south-westerly direction) can easily be found by applying trigonometry as shown in the illustration.

-
- (212) As the aircraft progresses from Milwaukee to Des Moines, the computer monitors any accelerometer count change. If negative counts are received from the "side" accelerometer, the computer knows the aircraft is going north. It is immediately displayed as an error, and the pilot will turn south so that the side accelerometer will be incremented again to compare favorably with the predetermined routing.

-
- (213) If the forward accelerometer senses an acceleration in the positive direction, this means that the aircraft has slowed down. In this case, the total time of flight will be increased or the aircraft will be made to speed up and regain its original speed plus make up for lost time by increasing the speed slightly.

(210)

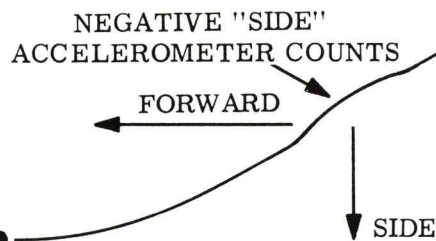


(211)

SINCE THE PLANE IS TRAVELING AT 150 MI/HR IN A WESTERLY DIRECTION, AND 90 MI/HR IN A SOUTHERLY DIRECTION THE TRUE VELOCITY IN A SOUTH-WESTERLY DIRECTION CAN BE SOLVED AS

$$\begin{array}{l} 150 \text{ MI/HR} \\ 150^2 = 22,500 \\ 175 \text{ MI/HR (APPROX.)} \\ \sqrt{30,600} = 175 \text{ (APPROX.)} \\ 90 \text{ MI/HR} \\ 90^2 = 8,100 \end{array}$$

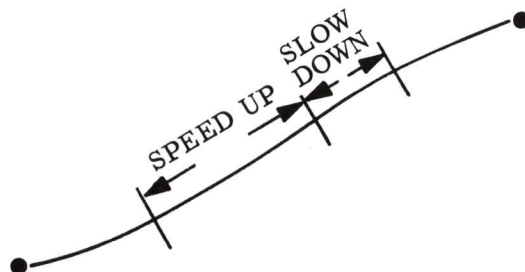
(212)



The direction of movement of the vehicle is determined by a given accelerometer count being incremented or decremented.

- A. True
- B. False
- C. ----
- D. ----

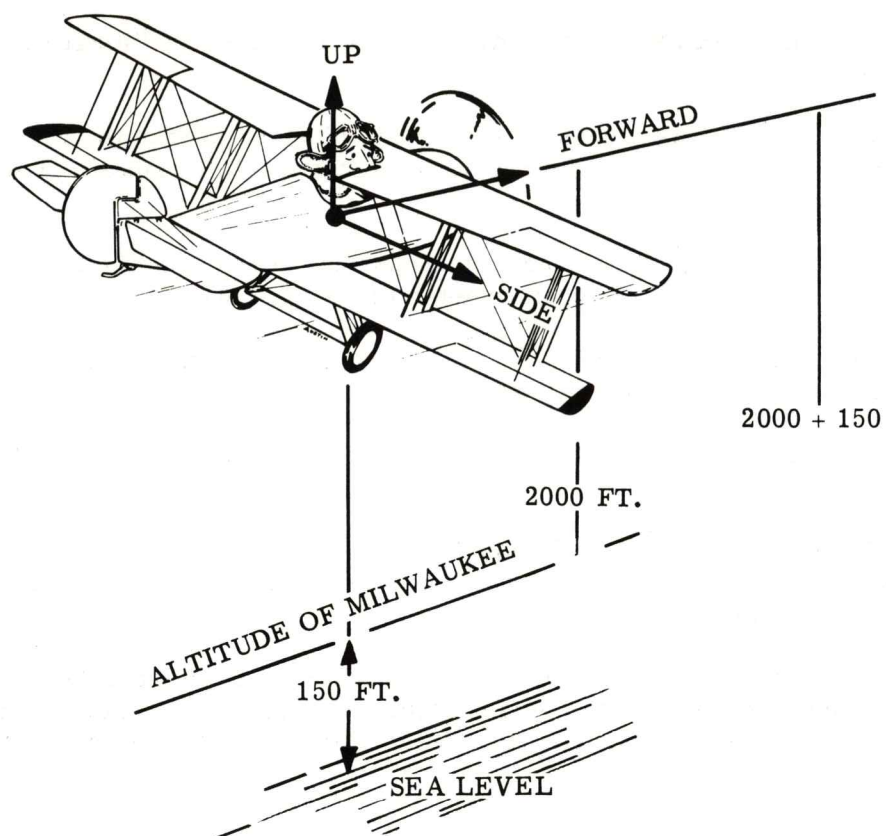
(213)



TURN SELECTOR TO POSITION 6

- (214) We haven't mentioned the "up" accelerometer. If we have a conventional barometric or radio altimeter on board the aircraft, then we probably won't need this particular accelerometer for this mission. If, however, altitude information is desired it could be derived from the "up" accelerometer. Any vertical acceleration that the aircraft undergoes will be sensed by this up accelerometer. The computer would calculate the vertical distance by using time and velocity information. This vertical distance would be the altitude of the aircraft above the start point. If true altitude above sea level was desired, the computer would simply add, to the indicated altitude, the altitude of Milwaukee above mean sea level.

(214)



TURN SELECTOR TO POSITION 7

(215) REVIEW OF EARTH NAVIGATION

We have discussed some basic navigation which concerned itself with travel over the earth.

We found that it was necessary to identify the start point of the flight not only by latitude and longitude but also by directing the stable member to a specific pre-departure situation.

We aligned the stable member so that the "up" accelerometer was parallel to gravity and the forward accelerometer was aligned with east.

The accelerometers were used to establish a horizontal plane, thus the positioning of the up accelerometer.

Gyro compassing was used to establish an easterly heading for the forward accelerometer.

We found that once the stable member was erected to an exact known position, and the computer had the necessary flight information, that the actual flight was quite simple.

The computer simply collected the actual data received from the accelerometers, and compared this data to the ideal data in its memory. On the basis of this comparison, the computer issued directional information to the pilot.

(215)

SPACE FOR ADDITIONAL NOTES:

TURN SELECTOR TO POSITION 8

(216) SOME BASIC TECHNICAL PROBLEMS

Let's stop a minute and take another look at our method of erecting the system and our flight. There are some points that were intentionally omitted for the sake of clarity. Can you think of some considerations that were omitted that would, if really omitted, result in serious errors in system operation?

-
- (217) How about while we were gyro compassing. The number 3 gyro was used as a nulling device. We decided that if gyro 3's input axis was pointed either east or west the gyro would not feel the effect of earth position. How about the other two gyros? They would feel some portion of earth rotation thus develop an output which would result in stable member displacement. We will not develop a method of compensating for this error build up but rather will simply state that compensation is required and provided.

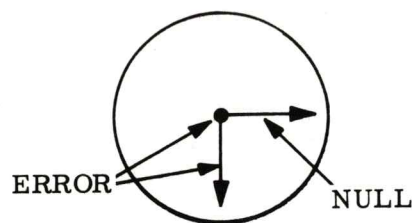
-
- (218) While the accelerometers were busy leveling the stable member we said that the gyros had not been started. . . . we fibbed a little bit. They really were running, but they were "caged". This means that the gyro output is not routed to the gimbal torque motors but rather is routed right back into itself. The result is a "frustrated gyro" that's telling itself not to do what it did.

-
- (219) Another problem that we neglected was during flight. In order for us to keep the "UP" accelerometer parallel to gravity during the entire flight, the stable member cannot stay in its original position throughout the flight, can it? The earth is round and gravity is directed toward the center of the earth at all positions around the earth. So, as we travel over the surface of the earth the stable member must be moved so that the "UP" accelerometer always points "up" for the geographical position of the aircraft. The computer knows the curvature of the earth and the aircraft's rate of travel over the earth. On the basis of this information the computer will send torquing signals to the appropriate Gimbal Torque Motors to maintain the "up" accelerometer in the local vertical position.

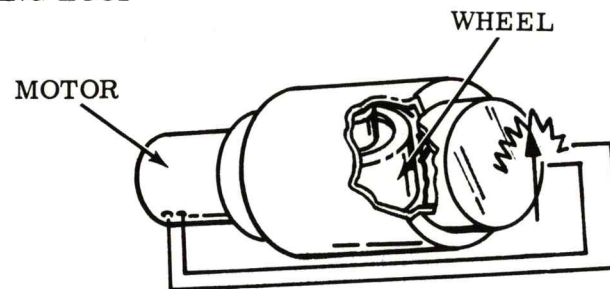
(216)



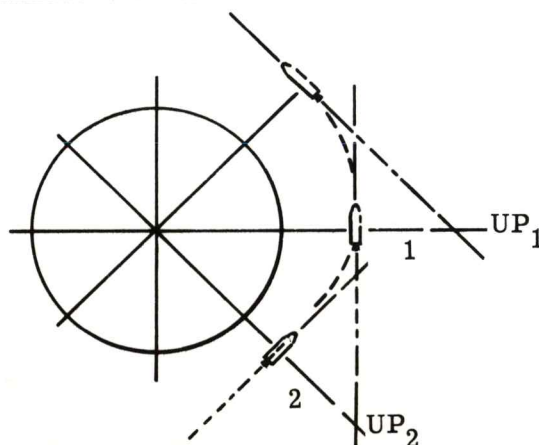
(217)



(218) GYRO CAGING LOOP



(219)



The stable member must be moved as the vehicle travels over the earth so that:

- A. the side accelerometer forward.
- B. the forward accelerometer points up.
- C. the up accelerometer will always be parallel to local gravity.
- D. none of the above.

TURN SELECTOR TO POSITION 9

- (220) There are other considerations that must be incorporated into a functional system such as Coreolis effect, Schuler Tuning, time response of loops and others. Discussion of these topics is not within the scope of this book.

(221) BASIC CONCEPTS OF ASTRONAUTICS

In this, the space age, it becomes increasingly important for one to know the basic concepts of astronautics. How are orbits determined? What applications of Inertial Guidance are being used? What are some of the techniques presently used for orbital and post orbital navigation? We will discuss these topics in the remainder of this text. It is inevitable that we use mathematics to describe some phenomenon. We will, however, keep the mathematics to a minimum and will describe each equation in words so that a limited mathematics background shouldn't prevent one from understanding the bulk of the material.

-
- (222) A discussion of astronautics necessarily involves a review of conic sections. If you are familiar with conic sections proceed to frame 235. If not continue to the next frame.

-
- (223) If a cone is "sliced" by a plane, the line of intersection of the cone and the plane forms a geometric shape which is determined by the way the plane cut the cone.

(220)

(221)

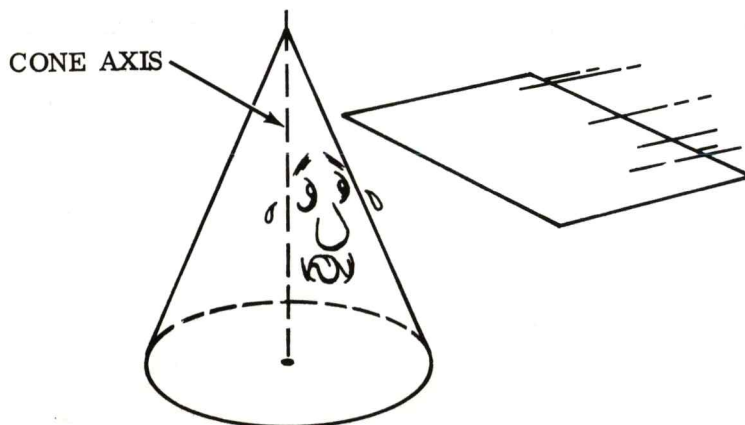
LET'S DISCUSS A LITTLE "BUCK ROGERS" STUFF.



(222)

IF YOU KNOW ABOUT CIRCLES, ELLIPSES, PARABOLAS AND HYPERBOLAS THEN PROCEED TO FRAME 235.

(223)



TURN SELECTOR TO POSITION 10

- (224) If the cone is cut in such a way that the cutting plane is perpendicular to the cone axis the resulting geometric figure will be a circle. (1) The size of the circle will depend upon the location the cutting plane penetrated the cone.

-
- (225) If the cone is cut at an angle other than 90° to the cone axis, three different geometric configurations could result depending upon the angle of penetration to the cone axis.

-
- (226) If the angle of penetration is not 90° and is greater than $1/2$ the apex angle (angle required to make the plane parallel to the sides of the cone), an ellipse will result. (2)

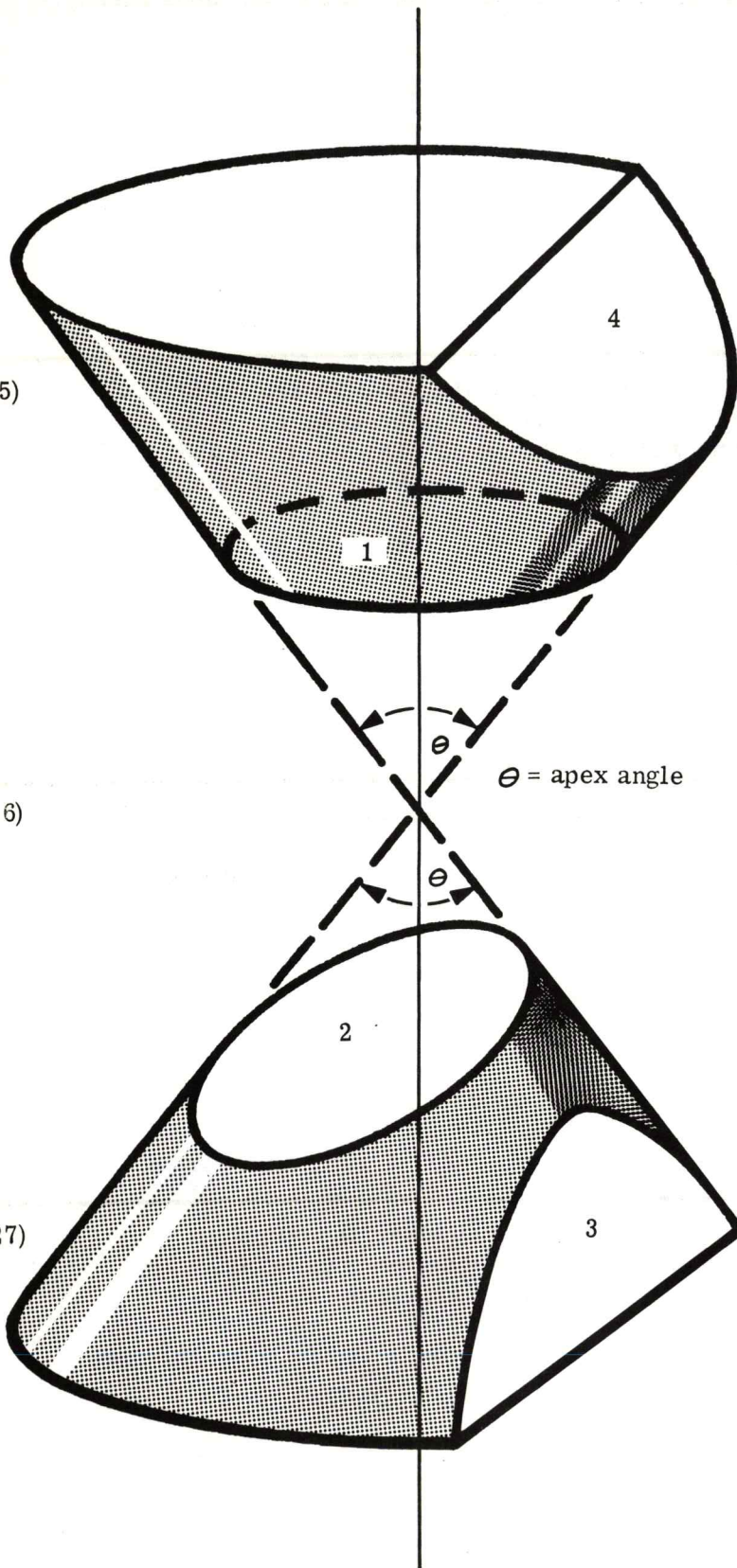
-
- (227) If the penetration is parallel to the side of the cone, (equal to $1/2$ the apex angle) then the resulting figure is a parabola. (3)

(224)

(225)

(226)

(227)



A plane intersecting a cone perpendicular to the cone axis will result in a:

- A. square.
- B. triangle.
- C. circle.
- D. hyperbola.

BY STUDYING SEVERAL INTERSECTIONS OF A PLANE THROUGH THE CONE. . . . WE WILL SEE VARIOUS GEOMETRIC CURVES RESULT.

If an intersecting plane develops an angle less than 90° and greater than $\frac{1}{2}$ the apex angle a/an _____ results.

- A. hyperbola
- B. eclipse
- C. circle
- D. ellipse

A parabola results when the intersecting plane is _____ the side of the cone.

- A. perpendicular to
- B. intersecting
- C. none of these answers are correct.
- D. parallel to

TURN SELECTOR TO POSITION 11

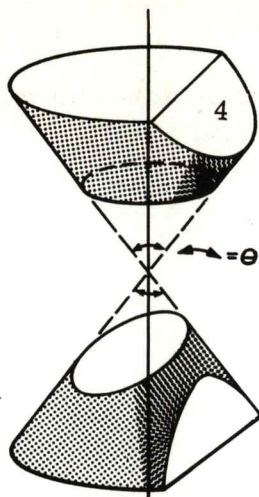
- (228) The last section is a hyperbola which is generated when the plane is passed through the cone at an angle to the cone axis, which is greater than $1/2$ the cone apex angle. (4)

-
- (229) Each of these four conic sections warrants consideration in space applications. The circle and ellipse will prove to be our major concern because it is in these two configurations that space orbits will be categorized. The hyperbola and parabola are applied in escape trajectories and will only be mentioned briefly.

-
- (230) Let's take a closer look at the ellipse. It has some unique characteristics that will be useful in analyzing basic orbits. These unique characteristics can be described by use of certain parameters which will, in turn, describe the shape of the ellipse.

-
- (231) Referring to the illustration, we define two lines which bisect the ellipse in the vertical and horizontal direction. The vertical bisector is called the minor axis and the horizontal line is called the major axis of the ellipse.

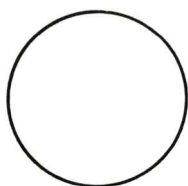
(228)



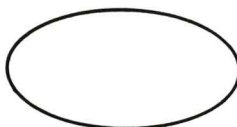
When the intersecting plane is parallel to the cone axis a _____ results.

- A. none of these answers are correct
- B. hysteresis loop
- C. circle
- D. hyperbola

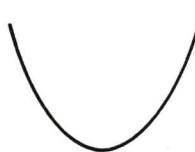
(229)



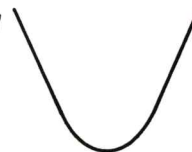
CIRCLE



ELLIPSE

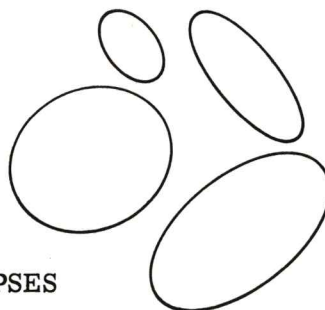


PARABOLA



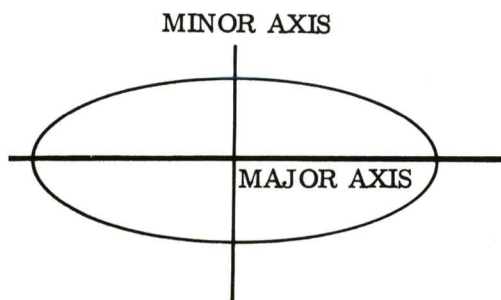
HYPERBOLA

(230)



ELLIPSES

(231)



The horizontal axis shown in the illustration is referred to as the _____ axis.

- A. major
- B. minor
- C. ----
- D. ----

TURN SELECTOR TO POSITION 1

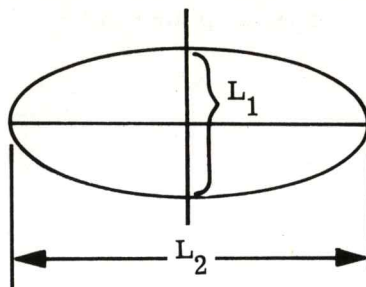
- (232) The length of these axes (L_1 and L_2) describe the shape of the ellipse. If only L_2 increases then the ellipse is "stretched out". If only L_1 is increased then the ellipse becomes "fatter".

-
- (233) A closer look at the ellipse will show that it is constructed from two sets of two circles of radius, r_1 and r_2 . The centers of circles of radius r_1 are important to us.

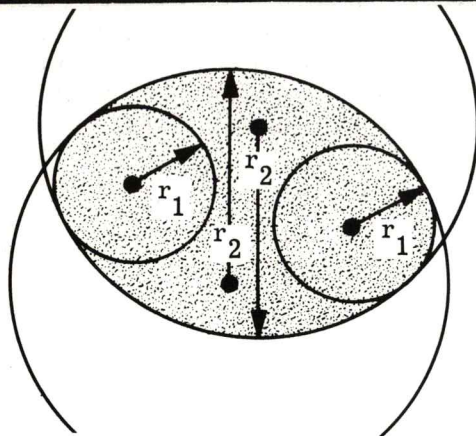
-
- (234) The centers of the end circles with radii of r_1 are called the focus points of the ellipse. The major axis of the ellipse passes through the foci of the ellipse.

-
- (235) Before we go any further let's give meaning to what we have already learned about the ellipse. Did you know that every planet, including the earth, follows an elliptical path around the sun? Did you further know that the sun is located at one focus of the ellipse that each planet travels?

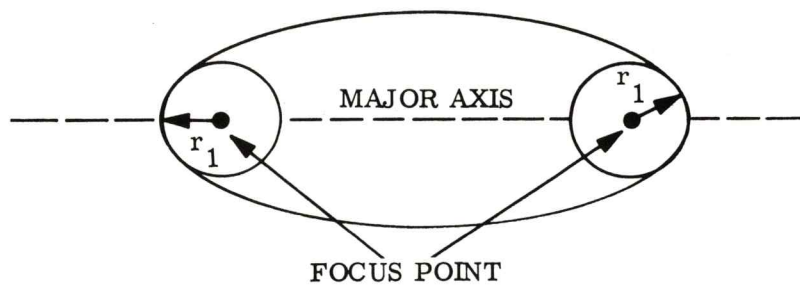
(232)



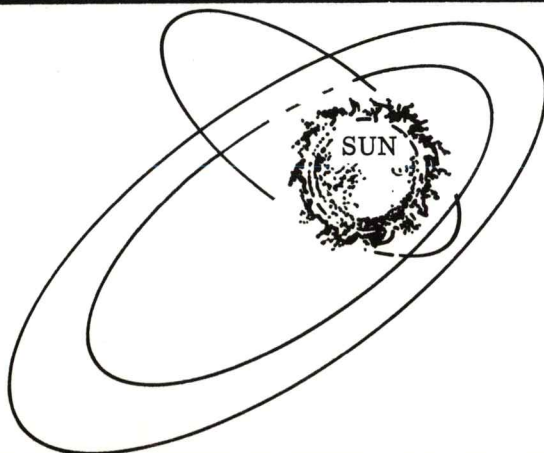
(233)



(234)



(235)



TURN SELECTOR TO POSITION 2

- (236) If you answered 'yes' to both of the questions in frame 232 then you know Kepler's* first law which states that the motion of all planets is an ellipse with the sun at one focus.

*More exciting news about
Kepler shortly.

-
- (237) The earth is very small as compared to the sun. A satellite in orbit around the earth is small as compared to the earth. The characteristics of the earth orbit about the sun are very similar to the satellite orbit about the earth. The earth is at one focus of the satellite's elliptical orbit. (This does not imply that satellites must be in elliptical orbits at all times.)

-
- (238) As long as we are discussing elliptical orbits, this would be a good time to define apogee and perigee of an elliptical orbit.

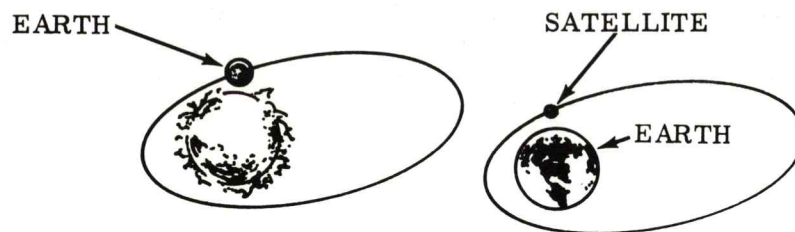
Apogee is the point on the ellipse which is farthest from the reference focus (earth).

Perigee is the point on the ellipse which is closest to the reference focus point (earth).

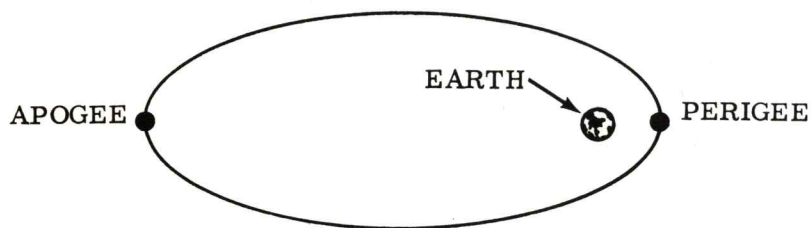
-
- (239) The apogee and perigee along with the focus points all lie on the major axis. Thus, the length of the major axis of an elliptical orbit is the sum of the apogee and perigee distances.

(236)

(237)



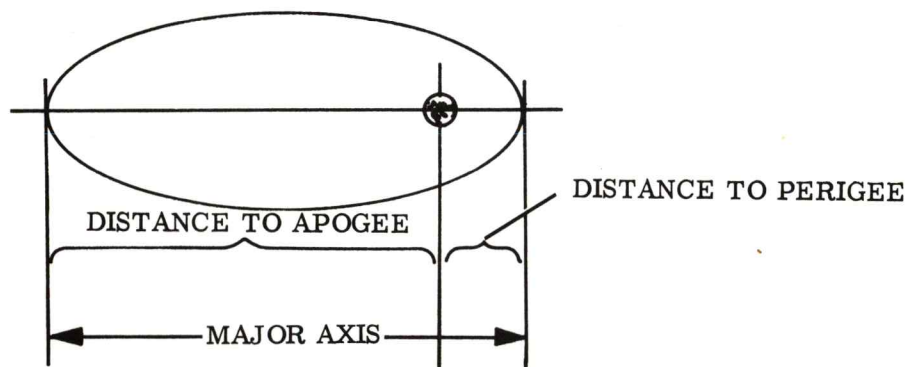
(238)



When a missile places a vehicle in an elliptical orbit about the earth, a point on the ellipse which is farthest from the earth is called the:

- A. apogee.
- B. axes.
- C. perigee.
- D. limit point.

(239)



(240) KEPLER'S CONTRIBUTION

We mentioned the name "Kepler" back in frame 236, and didn't persue it any further. Let's take a few minutes and discuss this man Kepler and what he did for us.

-
- (241) Johannes Kepler (1571 - 1630) was a German mathematician and astronomer. His early ambition was to be a minister but fate decreed otherwise. He was offered ever increasing challenges in the field of mathematics and astronomy, and, as a result of his efforts, published 33 works on these subjects.

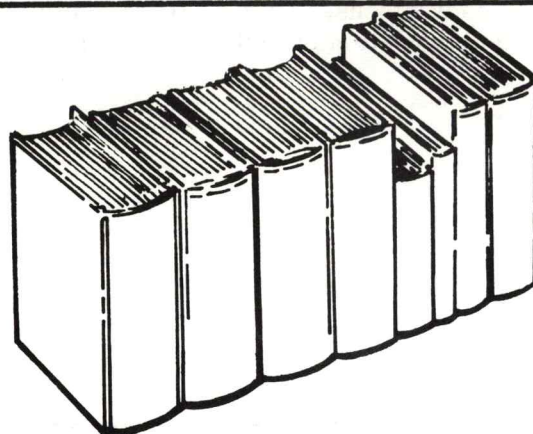
-
- (242) One of these published works was called "De Harmonia Mundi". This work, published in 1619, is of significant interst to us because it was from this book that Newton started his studies which later were contained in his "Principia" (see frames 1 through 8). Little did Kepler know that one 12 year old Isaac Newton was going to later prove his theories.

-
- (243) Kepler's major contribution to todays space applications is his three laws of planetary motion which are named for him and which were proved by Newton after his death.

(240)



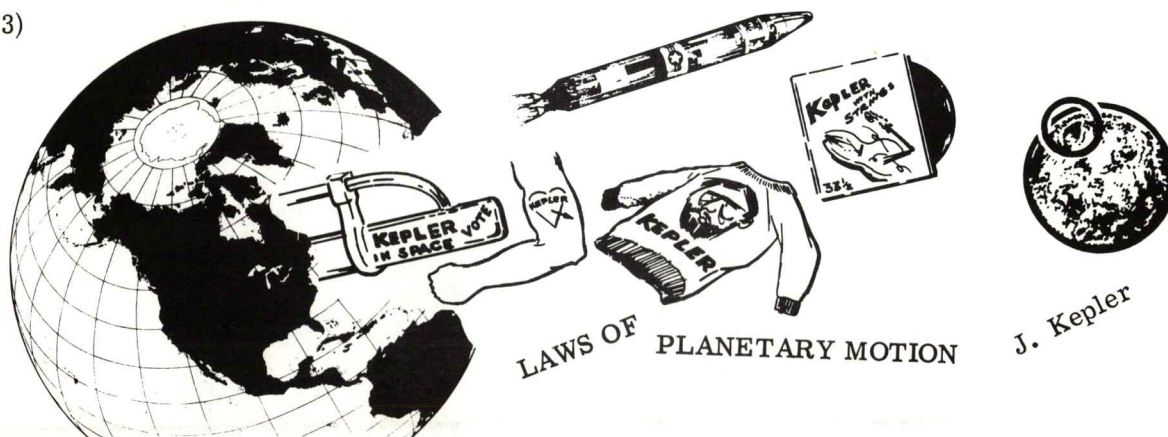
(241)



(242)



(243)



TURN SELECTOR TO POSITION 4

(244) Kepler's three laws of planetary motion are:

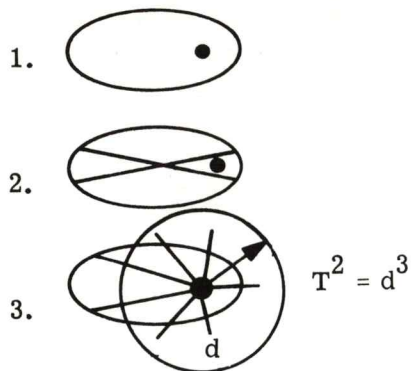
- I. The orbit of each planet is an ellipse with the sun at one focus.
- II. The line which joins a planet to the sun sweeps over equal areas in equal intervals of time.
- III. The squares of the periods of the planets are proportional to the cubes of their mean distance from the sun.

(245) Law I we have, in essence, already discussed. Kepler was able to deduce this law by astronomical tables and observations which were available to him.

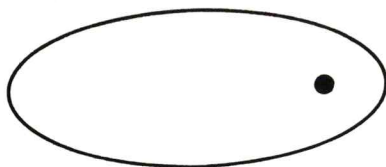
(246) Law II is a very functional law for our applications. It says that the earth, as it travels in its elliptical path will "sweep out" equal areas of the ellipse in equal periods of time. This really gives us velocity information, doesn't it?

(247) If the earth is traveling in an ellipse about the sun so that area 1 is swept out in the same time as area 2, then area 1 is equal to area 2. In order to accomplish this, the earth must go faster when it is closer to the sun and slower when it is farther away from the sun because to go a longer distance in equal time as a shorter distance, you must go faster.

(244)



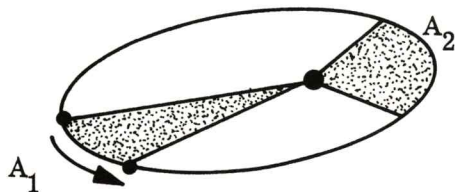
(245)



Kepler's first law defines:

- A. the shape of the earth.
- B. the planets path around the earth.
- C. the orbital path of planets.
- D. the shape of the sun.

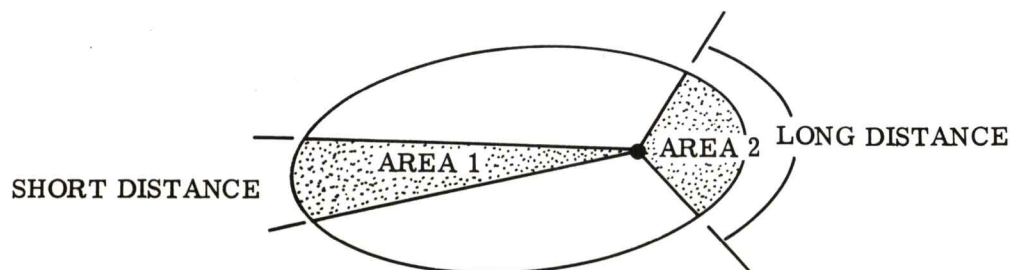
(246)



Newton's second law has to do with:

- A. time
- B. time, velocity and area.
- C. area.
- D. velocity.

(247)



AREA 1 = AREA 2

TURN SELECTOR TO POSITION 5

- (248) It has been implied and now is stated. . . . Kepler's laws are equally as accurate when applied to satellites orbiting the earth as it was when considering the earth's orbit about the sun. Thus, we can say that the satellite in an elliptical orbit will be going its slowest speed when at apogee and its fastest speed when it is at its perigee.

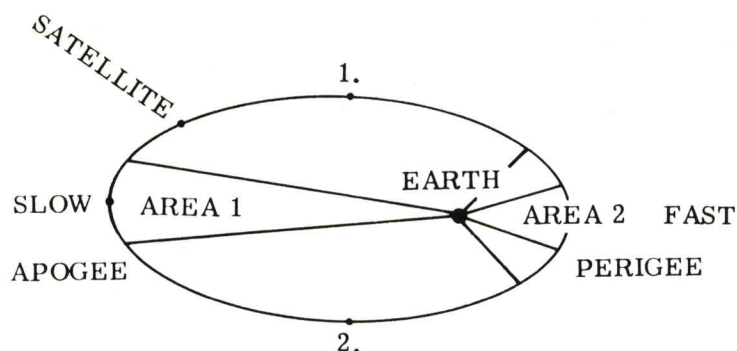
-
- (249) Kepler's third law is a statement of the time it takes an orbiting body to make one revolution about the central body. In the case of the earth-sun the central body is the sun. The orbiting earth, as we know, takes approximately 365 days to make one orbit. In the case of a satellite orbiting about the earth, the earth is the central body and the time to make one orbit is determined by the mean altitude of the orbit.

-
- (250) The mean distance (average distance) of an orbit is determined mathematically and numerically is equal to one half the length of the major axis. (This is simply stated. Proof of this is left to the reader. Equal areas will assist in this proof.)

-
- (251) We have discussed the ellipse and the application of Kepler's laws to the ellipse. Let's talk briefly about the circle.

The circle is really a special case of the ellipse.

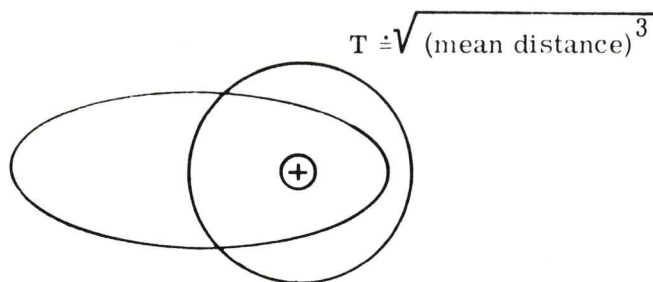
(248)



Assume apogee speed is minimum and perigee speed is maximum, then it sounds reasonable that points 1 and 2 on the ellipse have the same velocity.

- A. False
- B. True
- C. ----
- D. ----

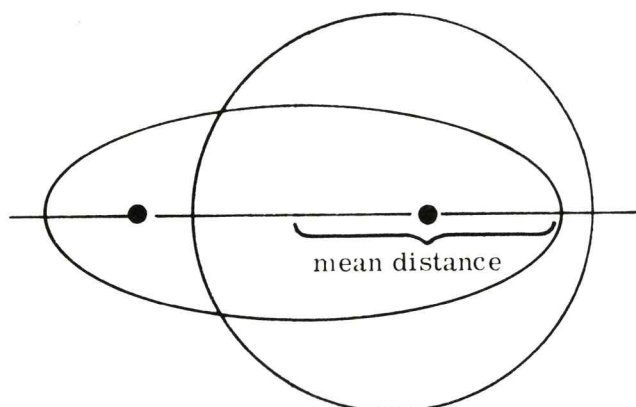
(249)



Kepler's third law relates:

- A. position of earth.
- B. time and the earth.
- C. time and distance.
- D. distance.

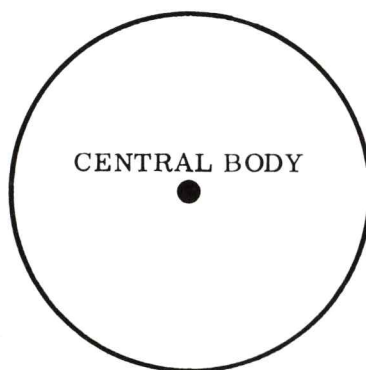
(250)



The mean distance a satellite is from the earth is:

- A. the major axis length.
- B. twice the minor axis.
- C. the semi minor axis.
- D. one half the major axis.

(251)



TURN SELECTOR TO POSITION 6

- (252) When the four points of an ellipse are located equal distances from the center, we have a circle. The major axis is the same length as the minor axis. The mean distance is the radius of the circle. Circular orbits are achieved by man made devices. Natural orbiting bodies are not found in circular orbits - so says Kepler's third law.

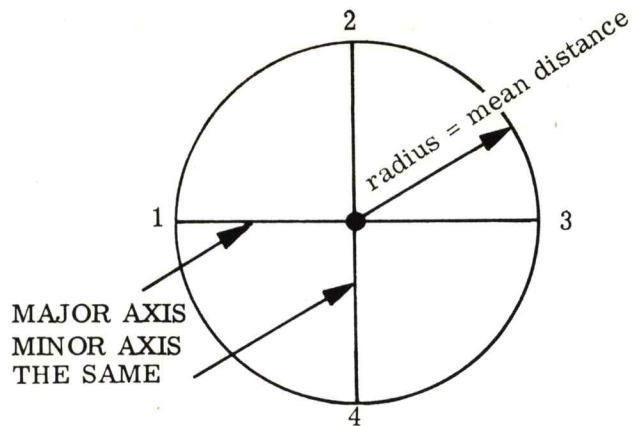
-
- (253) How do we achieve a specific circular or elliptical orbit with the use of an inertial guidance/navigation system? Can the system tell what type orbit we are in, and can it guide us into a specific orbit? Can it tell where, in an orbit, we presently are? It certainly can!

(254) ENERGY RELATIONSHIPS AND ORBITS

In order for us to understand the method used for orbital determination and orbital position finding, we will have to discuss briefly the energy relationships associated with different orbits. It is from the energy relationships that our inertial guidance/navigation system will be able to guide a vehicle into orbit, and continue to identify its position in the orbit.

-
- (255) If you are already aware of the concepts of potential and kinetic energy proceed to frame 264. If not, continue to the next frame.

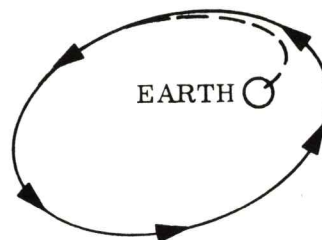
(252)



A circle is an ellipse with:

- A. no major axis.
- B. equal major axes.
- C. the two foci at one point.
- D. no focii.

(253)



PRESENT POSITION, TYPE
ORBIT, TIME ENROUTE, ETC.

(254)

ENERGY RELATIONSHIPS WILL BE USED TO UNDERSTAND BASIC ORBITS.

(255)

IF YOU CAN DEFINE KINETIC AND POTENTIAL ENERGY PROCEED TO FRAME 264.

TURN SELECTOR TO POSITION 7

(256) Before we can discuss types of energy, let's define energy as "the ability to do work". If a body contains energy, it has the capability of doing work. There are many forms of energy. All forms are categorized into two types - Kinetic and Potential.

(257) Potential Energy (PE) is the ability to do work by virtue of position or inherent capability. A can of gasoline has potential energy because with it we can do work when it is burned. A brick held over ones head has potential energy by virtue of its position.

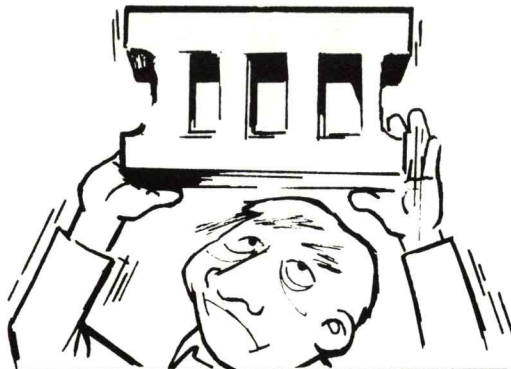
(258) Kinetic Energy (KE) is energy by virtue of motion. A moving body has kinetic energy because it can do work. For instance, when the man drops the brick that he was holding over his head, the brick, because of its downward motion, could do work.

(259) In order for us to have some sort of standard, let's assign a positive sign (+) to that energy which is doing something (kinetic) and a negative sign (-) to that energy which requires something to be done to it (potential).

(256)

ENERGY = THE ABILITY TO DO WORK

(257)



Potential energy is a static energy.

- A. True
- B. False
- C. ----
- D. ----

(258)



Knetic energy is dynamic in nature.

- A. ----
- B. ----
- C. True
- D. False

(259)

PE = -

KE = +

Kinetic energy is designated + because:

- A. it's more than PE.
- B. it's less than PE.
- C. it's equal to PE.
- D. it's a standard we picked.

TURN SELECTOR TO POSITION 8

(260) In our example of the man holding the brick over his head, the man is expending energy holding the brick up in the air. The amount of energy he is expending is proportional to the weight of the brick and the distance the brick is held up over his head. Since he is expending energy to give the brick potential energy, then it sounds reasonable to denote the bricks potential energy as a deficit (-) doesn't it?

(261) When he lets go of that brick, the potential energy starts to reduce because its distance over his head is becoming less. The downward movement of the brick is reducing the potential energy but is now introducing Kinetic energy by virtue of its movement.

(262) Kinetic energy is proportional to the weight of the brick (as was potential energy) and the square of the velocity (V^2). The faster it goes the more kinetic energy it possesses.

(263) The point that we are trying to make is that the sum of the potential energy and the kinetic energy for a given system is a constant. This sum is called total energy of the system. (Our system is the man, the brick and gravity.)

(260)



This has potential energy.

He's expending energy to give it potential energy.

(261)

STATIONARY



KINETIC ENERGY INCREASE

POTENTIAL ENERGY DECREASE

(262)

$$KE \propto m v^2$$

(263)

TOTAL ENERGY OF A GIVEN SYSTEM IS A CONSTANT.

$$KE + PE = TE = \text{CONSTANT}$$

TURN SELECTOR TO POSITION 9

- (264) We said that potential energy was assigned a negative sign because energy had to be expended in attaining it. (Man holding brick.) It is more correct to write the total energy equation taking these signs into consideration, thus:

$$T. E. = (KE) + (-PE)$$

This says the same thing but is more definitive according to our signed definitions.

-
- (265) The definition of mass (M) is: Weight (w) divided by the acceleration due to gravity (g). We will use mass in all our calculations rather than weight.

-
- (266) The relationships of Kinetic energy and Potential energy with respect to total energy is very important in orbit determinations. It is the energy, that an orbiting body has, that determines its orbital path.

(264)

$$TE = (+KE) + (-PE)$$

We use signs in the TE equation to:

- A. keep track of energy relationships.
- B. to keep you confused.
- C. to keep KE constant.
- D. to identify, by direction, the force.

(265)

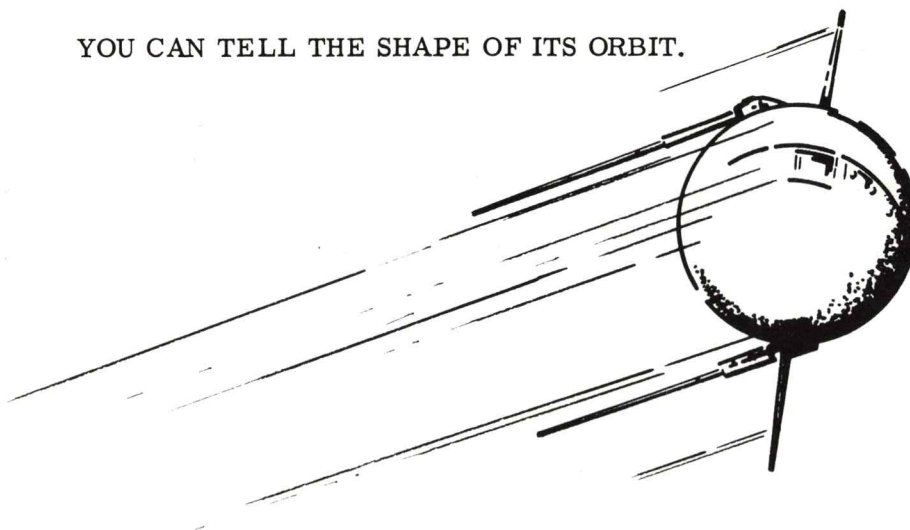
$$\frac{W}{g} = M$$

Given the value of gravity you could calculate the mass of an item by:

- A. B and C are correct.
- B. multiplying the weight of the object by gravity.
- C. adding the mass to the weight.
- D. dividing the weight of the object by gravity.

(266)

IF YOU KNOW THE AMOUNT OF KE AND PE A SATELLITE HAS, THEN
YOU CAN TELL THE SHAPE OF ITS ORBIT.



TURN SELECTOR TO POSITION 10

(267) Without the mathematical proof, let's look at the shaping of an orbit by total energy analysis.

(Keep in mind that there are an infinite number of similar shaped orbits like in the illustration. The orbits shown are just typical examples.)

(268) Orbit A is an ellipse with the earth necessarily at one focus. The total energy of the orbiting body is negative. This means that the potential energy is greater than the kinetic energy; in fact, one half the potential energy is much greater than the kinetic energy ($KE \ll 1/2 PE$).

(269) Orbit B is an ellipse with the earth at one focus. Total energy is negative and the kinetic energy is still smaller than one half the potential energy ($KE < 1/2 PE$). Any desired orbit which lies between A and B can be achieved by increasing the kinetic energy which exists in A. This could be done by increasing the velocity of the satellite (remember $KE \propto \text{mass} \times \text{velocity}^2$).

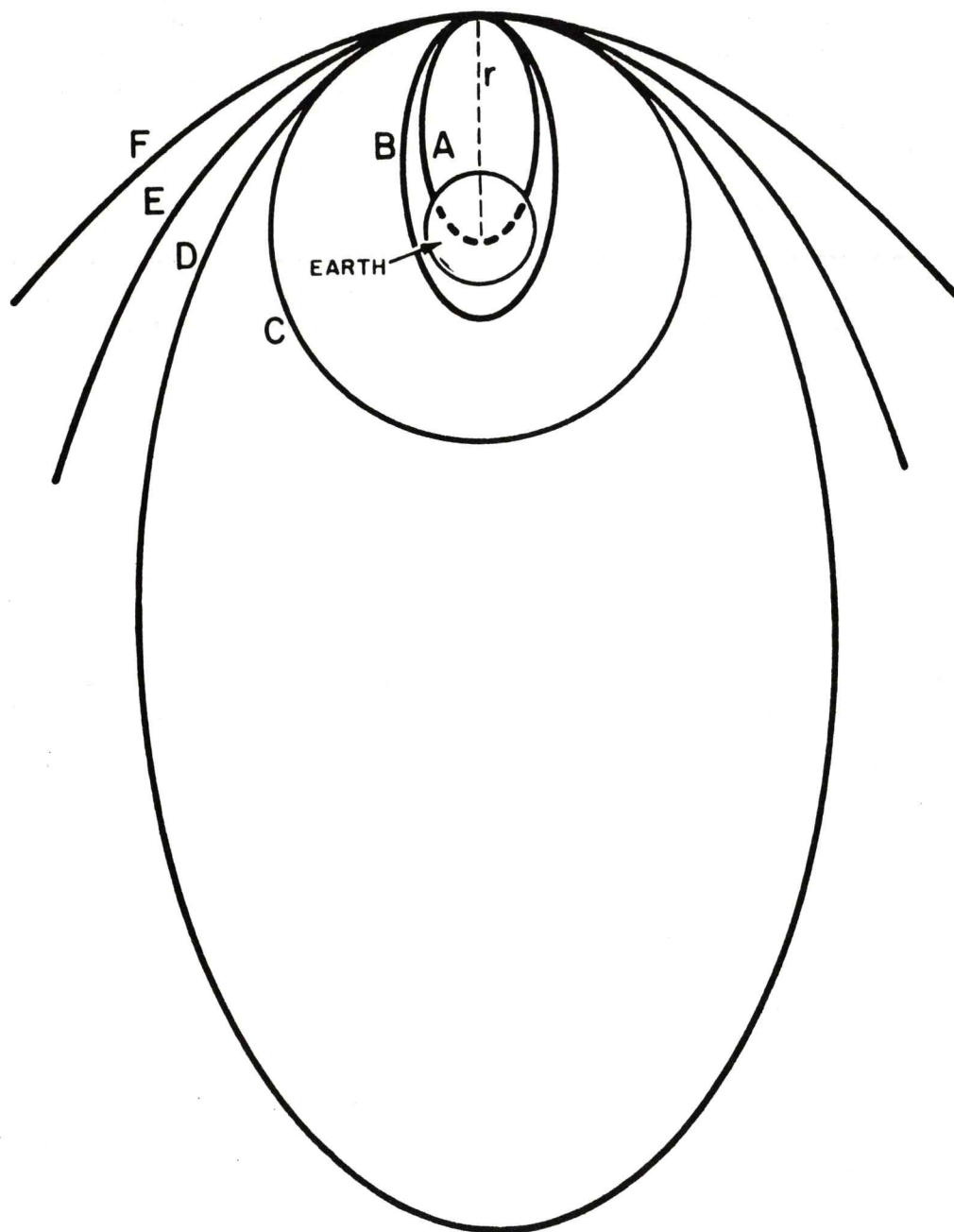
(270) Orbit C is a very unique orbit in that only when the kinetic energy is equal to one half the potential energy can this circular orbit be achieved ($KE = 1/2 PE$). The total energy of the system is still negative isn't it?

(267)

(268)

(269)

(270)



ENERGY TRAJECTORY

TURN SELECTOR TO POSITION 11

(271) What have we done so far? Starting at the dashed line labelled "r", we have pure potential energy. (The satellite is r distance from the center of the earth and is not moving. This is impossible to do, but for analysis purposes it is a good starting point.) The Kinetic energy is zero because the satellite isn't moving. Then we started to consider a movement of the satellite, thus introducing some kinetic energy. With very little KE some elliptical orbit would be followed. A sample was "A". As we increased the kinetic energy our ellipse grew larger (a sample was "B") until we reached a critical point where the kinetic energy was just exactly one half the potential energy. This resulted in the circular orbit (C).

(272) If we further increase the kinetic energy we again follow an elliptical path. This time our ellipse is outside the circular path as shown in "D". Our total energy is still negative because the kinetic energy is still less than the potential energy.

(273) At the point where our kinetic energy is increased to where it equals the potential energy, another unique situation occurs. The Total Energy of the system is zero and the orbital path is a parabola (E). This is an escape situation and can no longer be considered an orbit about the earth.

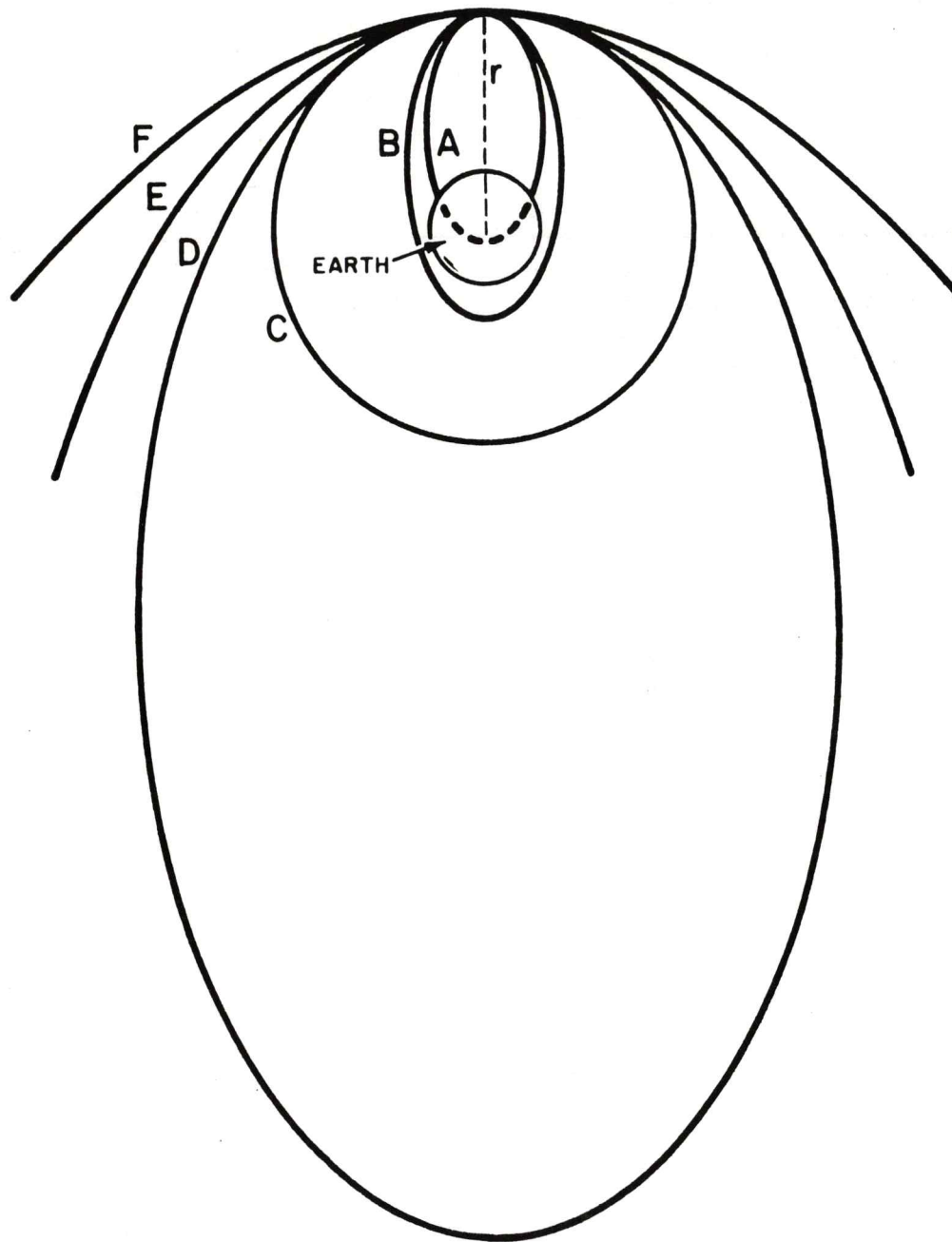
(274) As we further increase the kinetic energy, the total energy of the system becomes positive and the path that will be followed is called a hyperbola (F). Continued increase in velocity (KE) will cause progressively straighter lines than F.

(271)

(272)

(273)

(274)



ENERGY TRAJECTORY

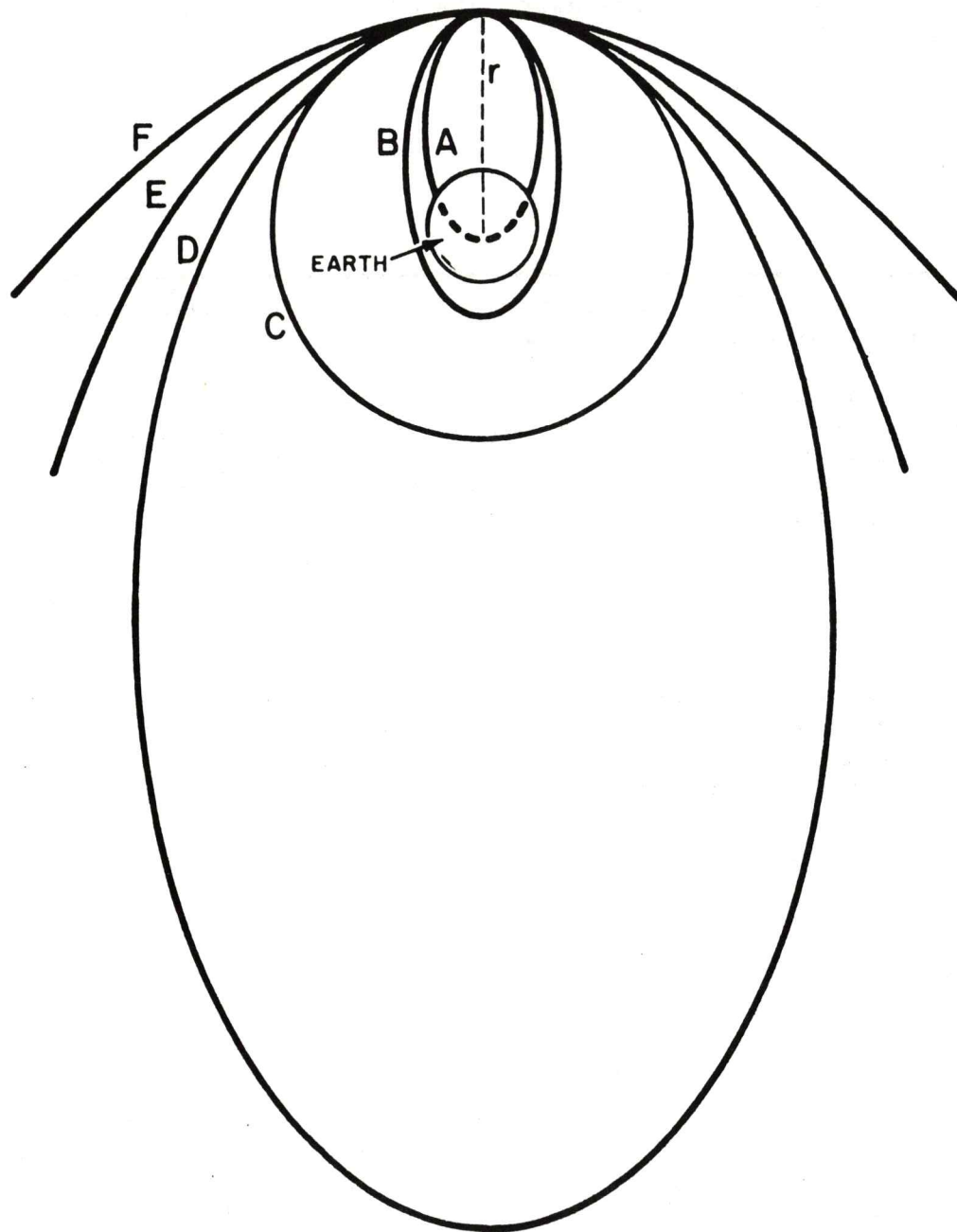
TURN SELECTOR TO POSITION 1

- (275) An example of the hyperbolic path is where a particle from space, moving at a very high velocity (high KE), would come close to the earth but would not enter an earth orbit. As it passed the earth, the earth's gravitational force would alter its path. The resulting direction change would appear as a hyperbola or, if the kinetic energy of the particle were exactly equal to the potential energy at its closest point to earth, a parabola.

-
- (276) The size and shape of each of the orbits discussed is determined by the energy relationships we mentioned. The apogee and perigee of an elliptical orbit can be predetermined. The appropriate total energy can be imparted to a given payload, by the missile, so that a specific orbit can be achieved.

(275)

(276)



ENERGY TRAJECTORY

TURN SELECTOR TO POSITION 2

- (277) Let's look at an ellipse again. According to Kepler's first law, the earth will be at one focus of the elliptical orbit of a satellite. His second law tells us that equal areas of the ellipse will be swept out in equal time means, as we pointed out earlier, that the satellite will be going faster at perigee (closer to earth) than at apogee (farthest away). Does this tie into our energy requirements?

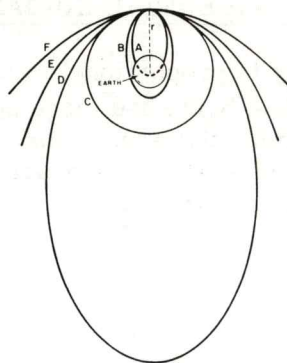
-
- (278) Yes -- of course. First, the total energy of the system must be constant. This total energy determines the orbital path.

At apogee we are farthest from the earth. Therefore, the potential energy is high. We also said, according to Kepler's second law, that the satellite is going slower. So this means the kinetic energy is less at apogee. The numerical reduction of the KE is equal, at any instant of time, to the numerical increase in potential energy.

-
- (279) At perigee we are closest to the earth. Therefore, the potential energy is minimum and the kinetic energy is maximum. The total energy, however, has the same numerical value as it did at apogee.

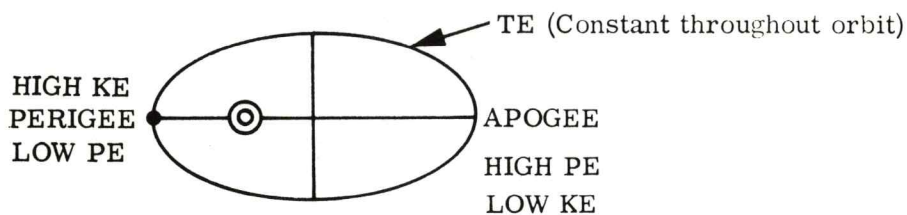
-
- (280) It is MANDATORY that we mention the fact that these orbits are determined on the basis of ideal conditions assuming the earth is a perfect sphere and no other forces, other than the earth's gravity, are exerted on the satellite. These are reasonable assumptions for our purposes, but not completely accurate.

(277)



ENERGY TRAJECTORY

(278) $TE = KE + (-PE)$

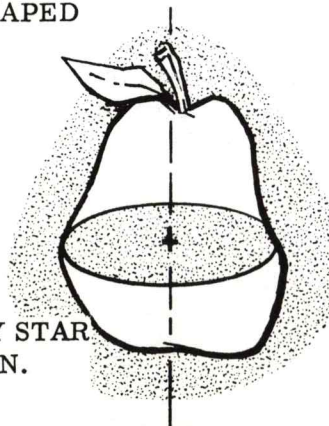


(279)

The kinetic energy of a payload is greatest at:

- A. perigee.
- B. apogee.
- C. lift off.
- D. orbit.

(280) EARTH IS REALLY PEAR SHAPED



WE'RE NOT THE ONLY STAR
IN THAT BLUE HEAVEN.

The analysis of orbits in this text:

- A. is based on assumptions.
- B. is based on a set of idealized parameters.
- C. none of these answers are correct.
- D. A and B are correct.

TURN SELECTOR TO POSITION 3

(281) ORBITAL DETERMINATION USING INERTIAL GUIDANCE/NAVIGATION

Do you recall that potential energy is proportional to the distance that the object is away from the central body? The brick had more potential energy the higher it got. The satellite has a given potential energy for its given altitude. Our point is that vertical distance and potential energy are related. Our inertial guidance/navigation system can determine distance. Can't it?

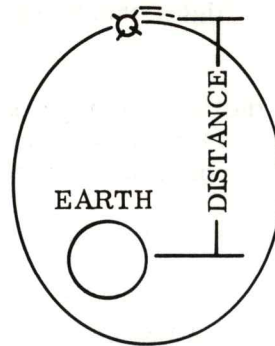
(282) Recall also that kinetic energy is proportional to velocity (V^2). Our inertial guidance/navigation system can determine velocity. Can't it?

(283) It follows then, that our inertial guidance/navigation system can guide a payload into a specific orbit by application of the accelerometer information to determine distance (altitude and velocity) for a given total energy relationship. The computer will know the velocity required for a specific kinetic energy and will know the distance required for a specific potential energy. It will then have, in its memory, the necessary data to put a payload into a specific elliptical or circular orbit.

(284) AN ORBITAL RENDEZVOUS FLIGHT

Let's take another flight. This time, instead of going to Des Moines, let's go into an elliptical orbit. The vehicle will be a rocket. Let's make the problem interesting by saying that we want to rendezvous with an already orbiting space vehicle.

(281)



Potential energy is a function of altitude therefore, the _____ will provide potential energy information to the computer.

- A. gyros and stable member
- B. gimbals
- C. stabilization loop
- D. accelerometers

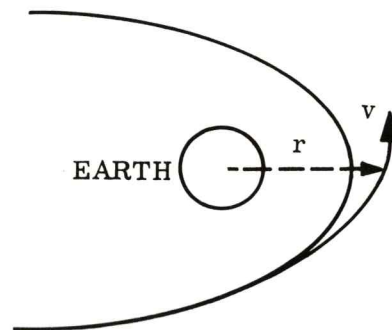
(282)



Kinetic energy is proportional to velocity squared. The _____ will provide the computer with this information.

- A. gyros
- B. accelerometers
- C. gimbal angle detectors
- D. missile

(283)

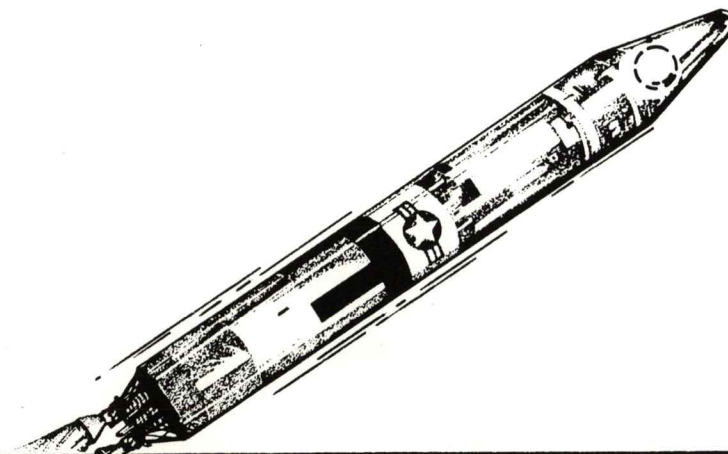


Distance = r

Velocity = v

$KE = 1/2 PE$

(284)

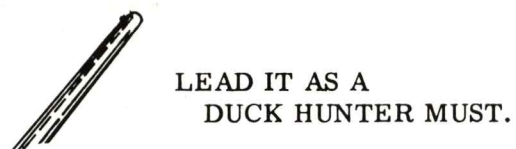
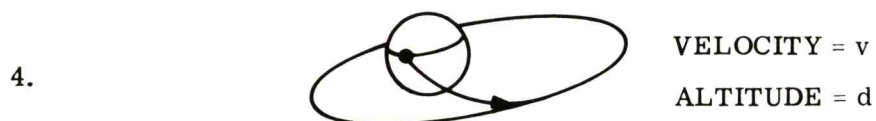
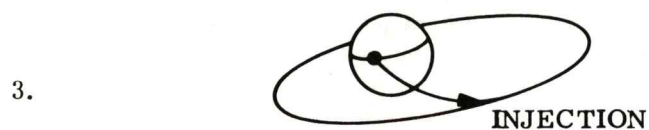
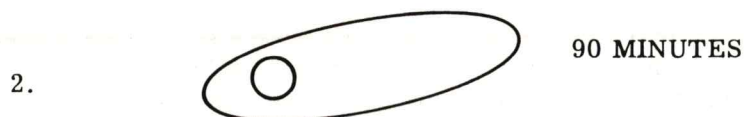
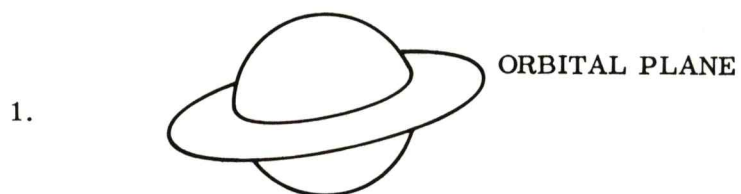


TURN SELECTOR TO POSITION 4

(285) In order for us to accomplish this flight, there are many things to be considered. Some of them are:

1. The orbital plane of the already existing satellite. Our payload will have to be launched into the same plane as the existing plane because of the rendezvous requirement.
2. The time it takes for the existing satellite to make one orbit.
3. The point in space that we want to inject our payload into orbit (its altitude and position).
4. The relationship of the kinetic and potential energy at this specific injection point. (This will determine the altitude and velocity required at the point of injection.)
5. The actual time it will take our missile to place the payload in orbit at the specific point in space. This time will be fixed.
6. Correlate the orbiting satellite's time of passage with the time of launch so that the satellite and our payload will meet at the predetermined point in space.

(285)



TURN SELECTOR TO POSITION 5

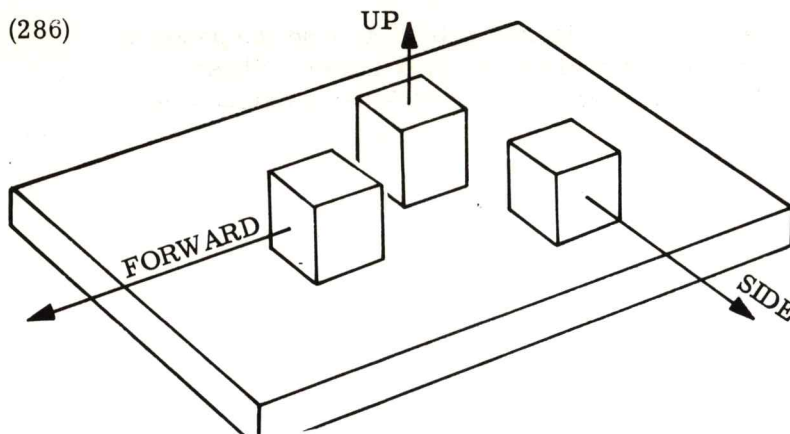
- (286) For us to accomplish our mission by using inertial guidance/navigation techniques, we must once again erect our platform so that we know exactly where we are launching from. This time we'll change our technique of erecting the system so that we can obtain a broader appreciation of system applications.

-
- (287) We will be using the same measurement unit that we developed earlier in the book. Since we are going to be launching vertically, our "up" accelerometer input axis will be aligned along the length of the missile. . . . parallel to gravity. The forward and side accelerometers input axis will be located in a local horizontal plane. (The names forward and side won't have much meaning in this problem because to go forward is to accelerate along the UP accelerometer input axis, but we will leave the names the same.) Let's go to the launch pad and get started erecting the system.

-
- (288) Instead of using the accelerometers to level the stable member as we did in our aircraft, we will use a vertical sensing element. This vertical sensing element is mounted on the stable member.

-
- (289) A Vertical Sensing Element (VSE) is simply a pendulum in a case. If this VSE is mounted on the stable member so that its longitude axis is perpendicular to the "side" and "forward" accelerometer input axis and parallel to the "up" accelerometer input axis, then we can use this VSE for leveling the stable member. Here is how!

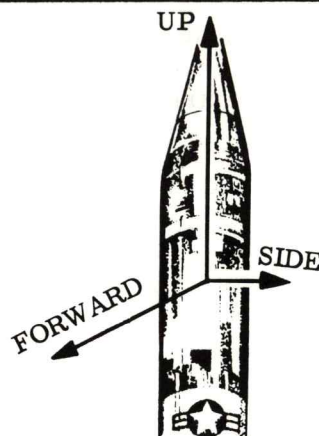
(286)



Knowing the latitude and longitude of the launch point is not sufficient, we must know:

- A. direction of local gravity.
- B. direction of local gravity and stable member azimuth.
- C. stable member gyro.
- D. stable member azimuth.

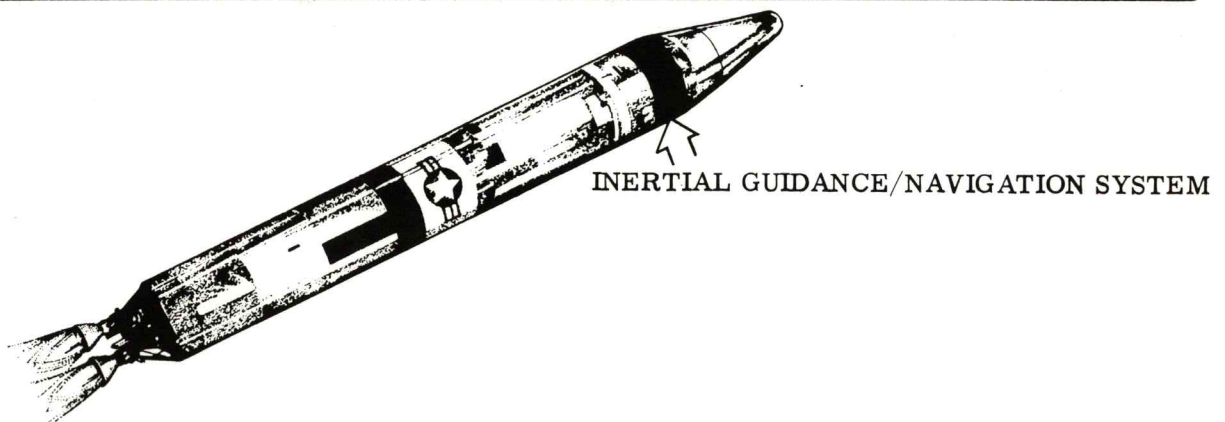
(287)



The up accelerometer input axis is located _____ to gravity prior to launch.

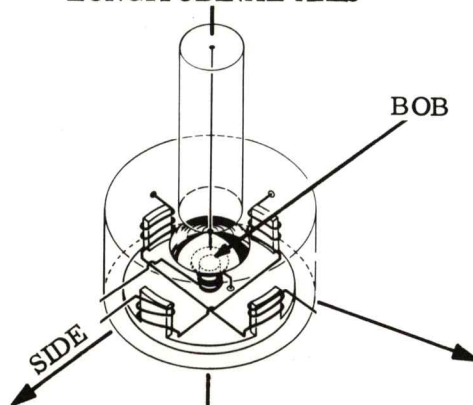
- A. perpendicular
- B. at an angle
- C. parallel
- D. A or C.

(288)



(289)

LONGITUDINAL AXIS



The VSE will be used to:

- A. establish a horizontal plane.
- B. level the gyro.
- C. level the pendulum.
- D. feed the output to the input device.

TURN SELECTOR TO POSITION 6

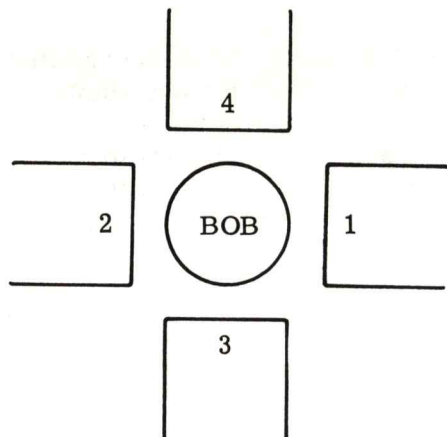
(290) Looking at the bottom of the VSE we see the pendulum "bob". Around the pendulum bob and attached to the case are four sensing devices (1, 2, 3 and 4). These sensing devices will indicate, electrically, which of the four sensing devices the "bob" is closest to.

(291) If the bob is closest to sensing device number 1, then an electrical current is generated by sensing device number 1. If the bob is between sensing device 1 and 3 then both number 1 and 3 will generate an electrical current.

(292) Keep in mind that the VSE is mounted on the stable member so that the sensing devices are in the plane of the "forward" and "side" accelerometer input axis. The pendulum is parallel to the "up" accelerometer input axis when the platform is level.

(293) The VSE is fixed in such a position so that an imaginary line connecting sensing devices 1 and 2 is parallel to the forward accelerometer input axis and an imaginary line connecting sensing devices 3 and 4 is parallel to the side accelerometer input axis.

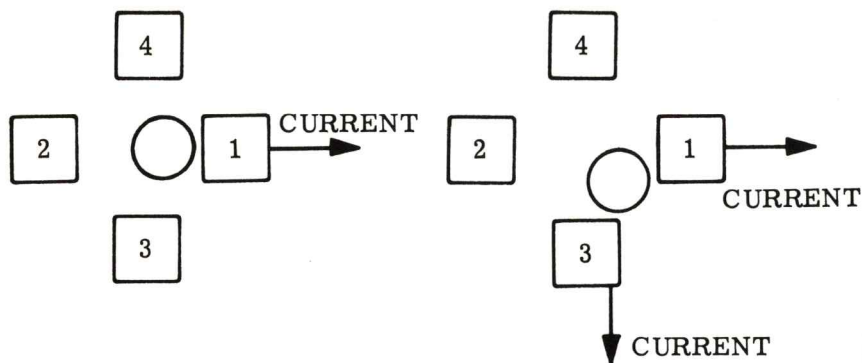
(290)



The pendulum bob is attached to the:

- A. sensors.
- B. measurement unit.
- C. VSE case.
- D. up accelerometer.

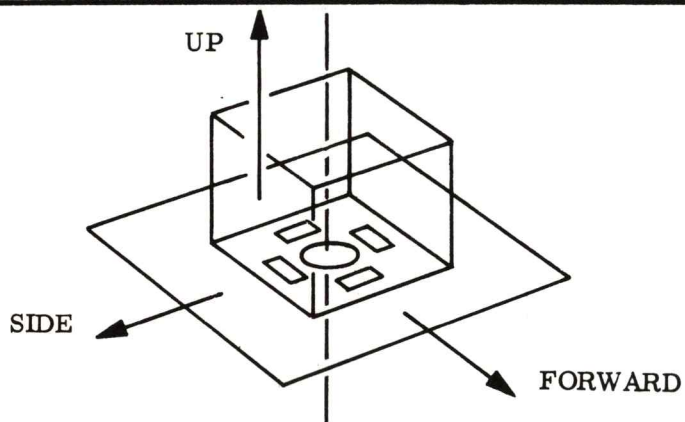
(291)



The geometric location of the VSE bob is identifiable by:

- A. periphery voltage.
- B. sensor movement.
- C. sensors position.
- D. sensor current.

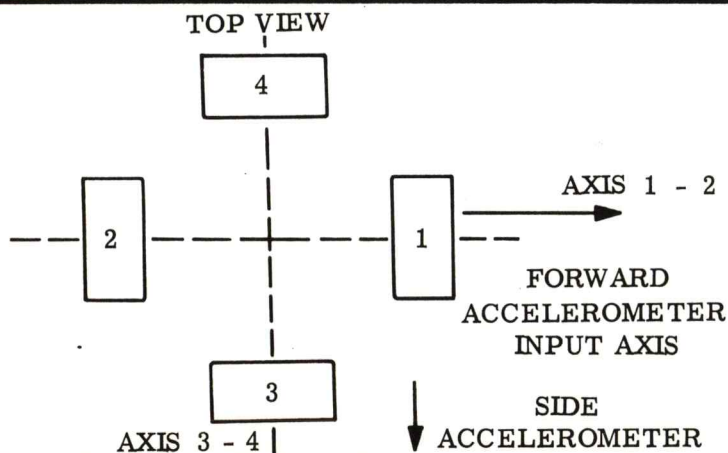
(292)



When the forward and side accelerometers have no output the pendulum bob will be geometrically:

- A. centered.
- B. toward one side.
- C. confused.
- D. nulled.

(293)



If the VSE is correctly positioned the forward accelerometer input axis is parallel to a line connecting VSE sensors:

- A. 1 and 4.
- B. 3 and 4.
- C. 1 and 2.
- D. 3 and 2.

TURN SELECTOR TO POSITION 7

- (294) We should have an idea about the orientation of the VSE now. Using our knowledge of the VSE, let's see how it can provide a horizontal reference for our stable member.

You should recall that the forward accelerometer input axis is parallel to an imaginary line which passes through sensors 1 and 2. Recall also that the gimbals around the stable member have their pivot point in line with the gyro input axes when the stable member is erected properly.

-
- (295) There are a lot of axes to correlate, but stay with it. We will now interject the VSE axes so that they will fit into the overall scheme. The imaginary line bisecting sensors 1 and 2 is parallel to (when the stable member is erected) the forward accelerometer input axis gyro 3 and gimbal axis 3.

-
- (296) The imaginary line connecting the centers of VSE axis 3 and 4 is parallel to gyro 1 input axis, side accelerometer input axis and gimbal axis 1.

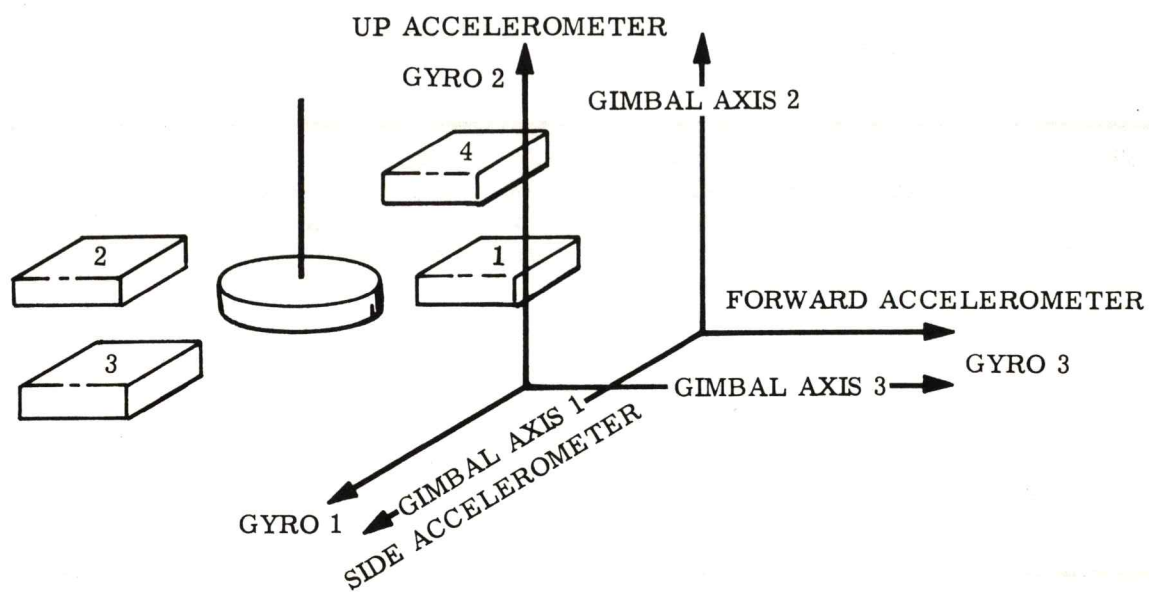
The pendulum of the VSE hangs parallel to the UP accelerometer, gyro 2 and gimbal axis 2.

FUN FRAME

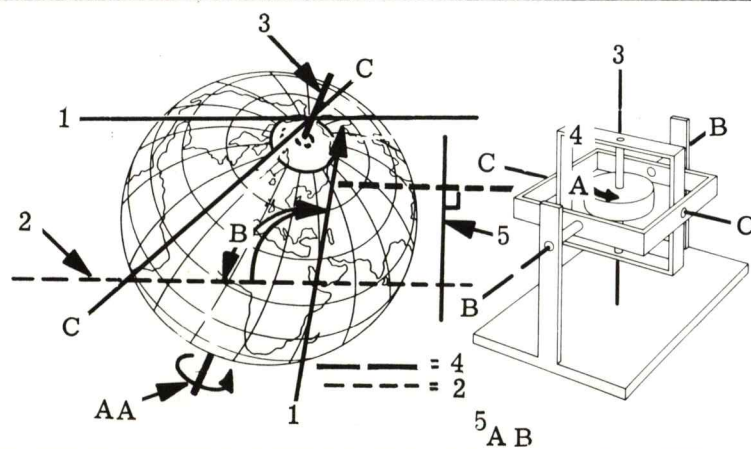
It can be plainly seen that axis 1 and axis 2 are parallel to axis 3 which isn't part of axis 20. This situation exists because axis parallel is 20 by the perpendicular center line of the imaginary. Therefore, the other isn't.

(294)

(295)



(296)



TURN SELECTOR TO POSITION 8

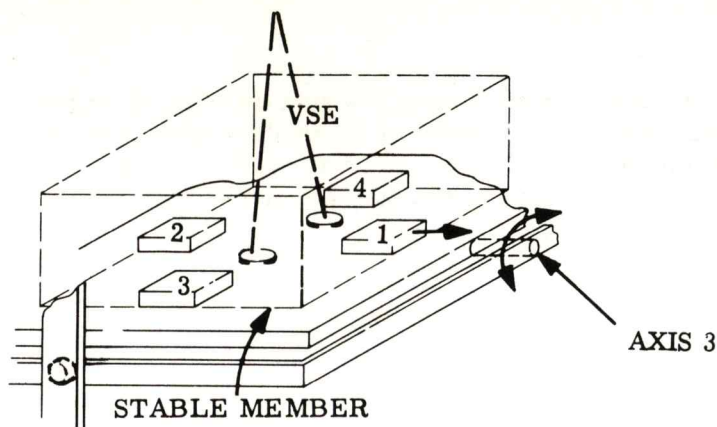
(297) If the stable member is out of level about gimbal axis 3, the pendulum bob will be displaced from its center position and sensor 3 or 4 will have an output. This output will be routed to the motor located on the gimbal axis and will cause the stable member to rotate in such a direction so as to force the pendulum midway between sensors 3 and 4.

(298) If the stable member is out of level about gimbal axis 1, then the pendulum bob will be closer to sensor 1 or 2. Again the current generated by the sensor closest to the bob will cause the motor on gimbal axis 1 to turn in such a direction so as to position the pendulum bob in the geometric center of sensors 1 and 2.

(299) It is reasonable that the bob (prior to erecting) would be in any random position not only off in one line. It sounds reasonable that both motors will be driving at the same time as a result of the current generated by poles 1 and 4 or 2 and 4 or 2 and 3 or 1 and 3. Regardless of where the pendulum starts, the stable member will be positioned in a horizontal plane. The pendulum will be parallel to gravity and the UP accelerometer input axis will therefore be parallel to gravity.

(300) The stable member is now positioned in a horizontal plane. This was accomplished by the accelerometers in our airplane example. In our missile, we use the VSE. Either approach is effective and accurate. The choice of which type device to use is up to the design specification for each situation. (You might wonder about the size of a VSE. The actual size is approximately the size of your little finger and weighs between 4 to 6 ounces.)

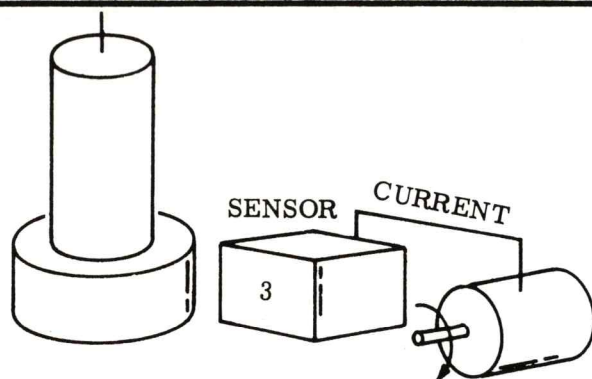
(297)



During erection, the VSE and accelerometer axes are aligned with the gyro and gimbal axes. The result is to drive a gimbal torque motor with the output of the:

- A. accelerometer.
- B. gyros.
- C. gyro sensors.
- D. VSE sensors.

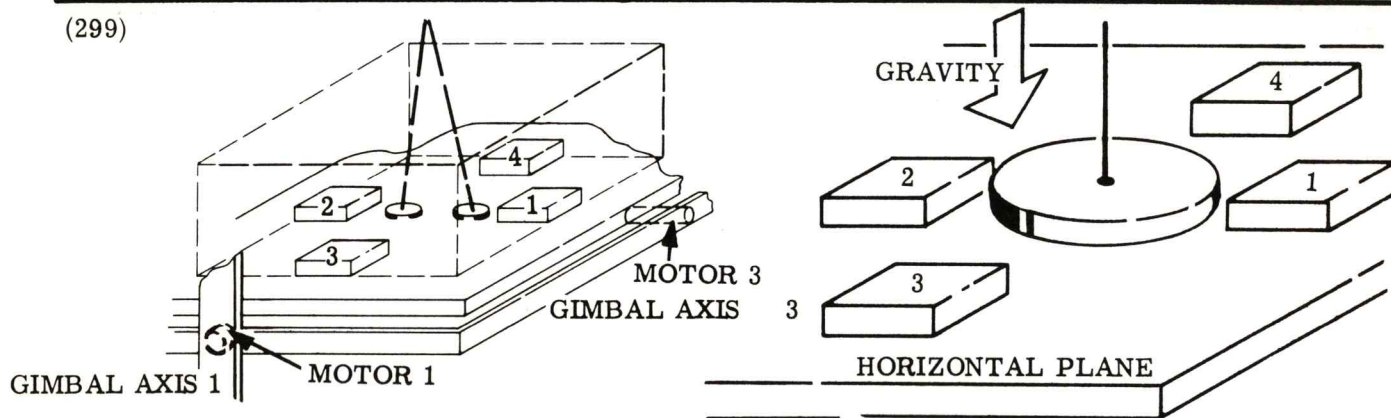
(298)



The direction in which the gimbal motor drives is determined by:

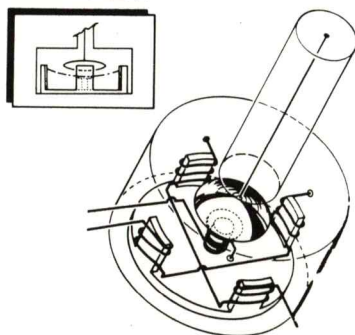
- A. the motors capability.
- B. the bob current.
- C. the sensor closest to the bob.
- D. the middle point.

(299)



(300)

SIDE VIEW



In order to "level" the stable member one could use:

- A. the accelerometers.
- B. a VSE.
- C. the accelerometers and VSE.
- D. a bubble.

TURN SELECTOR TO POSITION 9

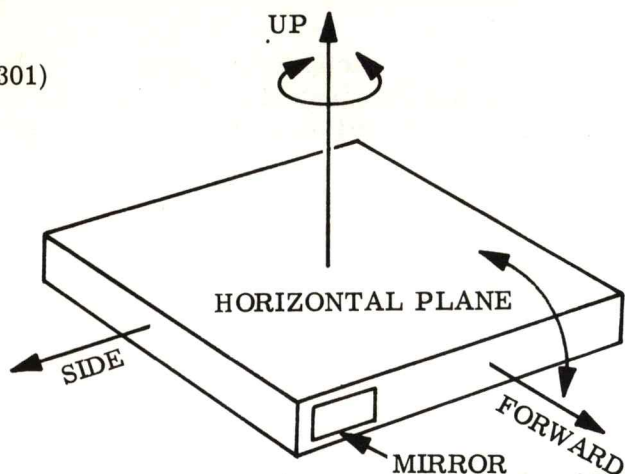
- (301) The next step in erecting the stable member is to align the accelerometers in the horizontal plane so that they point in a specific direction (azimuth alignment). We won't use gyro compassing this time as we did in the aircraft. We will use, instead, a mirror which is fastened to the edge of the stable member.

-
- (302) We make one assumption that is that the mirror is attached to the stable member so that the surface of the mirror is perpendicular (exactly) to the forward accelerometer input axis. (This means that the mirror is parallel to the side accelerometer input axis, doesn't it?)

-
- (303) Back on the ground we have a theodolite. A theodolite is an electro-optical instrument that is used to measure angles. It emits a light beam and has a photoelectric unit within it to detect the return of this light beam from a reflective surface.

-
- (304) If a mirror is placed in front of the theodolite, and the mirror is perpendicular to the incident light, then the light will be reflected right back to the theodolite. If the mirror is not perpendicular, only part or none of the light will return to the theodolite. The amount of electrical signal is inversely proportional to the amount of return light. (Most light, no electrical signal; no light, maximum electrical signal.)

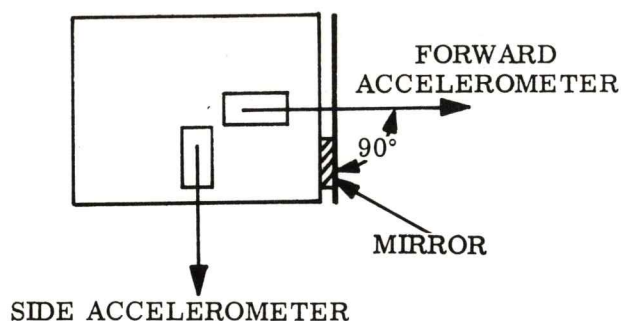
(301)



When the horizontal plane has been determined it is then necessary to:

- A. establish an exact line in that plane.
- B. launch.
- C. establish a vertical plane.
- D. establish rapport.

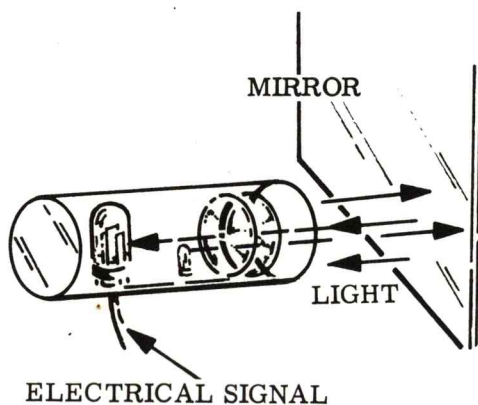
(302)



It is of paramount importance that the mirror be mounted exactly parallel to the _____ axis and perpendicular to the _____ axis.

- A. side accelerometer - forward accelerometer
- B. up accelerometer - side accelerometer
- C. gyro 1 - gyro 3
- D. A and C are correct.

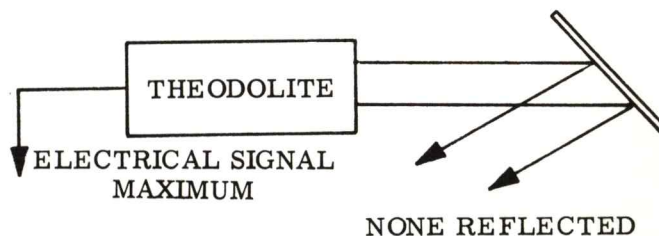
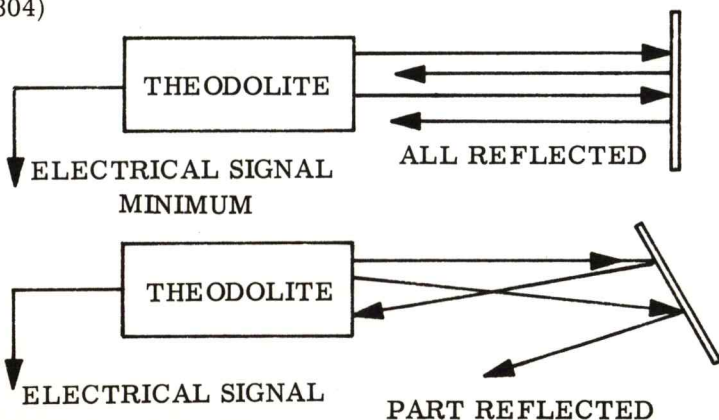
(303)



A theodolite has a:

- A. light source.
- B. all of these answers are correct.
- C. sensing system.
- D. photoelectric cell.

(304)



TURN SELECTOR TO POSITION 10

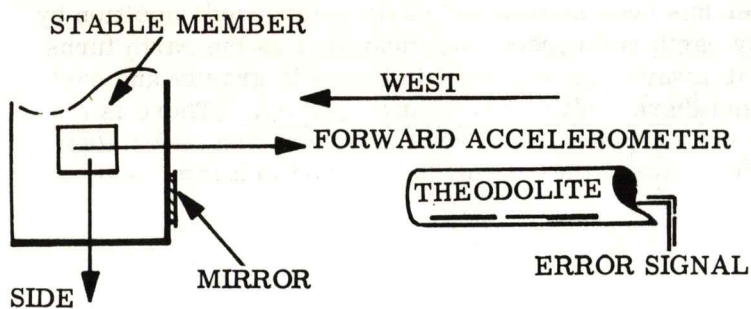
- (305) If the theodolite is oriented so that its light beam is pointed exactly west, then we can erect (align) our stable member in such a way that the forward accelerometer is pointing exactly east. (Side accelerometer will be south.)

-
- (306) Allow the stable member to be slowly rotated back and forth about gimbal axis 2 in the horizontal plane. At some point in the "searching" the mirror will be perpendicular to the theodolite light beam. As soon as the light beam is reflected back to the theodolite (captured), the motor which uses the error signal from the theodolite to guide its operation, stops turning. The stable member is now situated so that the forward accelerometer is pointing exactly east, and is in the horizontal plane.

-
- (307) The stable member is now erected (aligned). The inertial guidance/navigation system is ready to go. The computer has the flight profile in its memory, the measurement unit is "fired up" with the gyros and accelerometers up to speed. The accelerometers are sensing the force of 1 g and are giving the counts to the computer. The computer knows this is the acceleration due to gravity, not missile accelerations, so it doesn't calculate true velocity and distance - yet.

-
- (308) The time of launch is set so that the vehicle will intersect the orbiting body at the predetermined point in space. We have 10 seconds before launch time. Everything is "go", the final countdown is in progress. . . . 10 - 9 - 8 - 7 - 6 - 4 - "GUIDANCE GO INERTIAL". Let's mentally stop the countdown and see what the command from the launch officer "guidance go inertial" means to us.

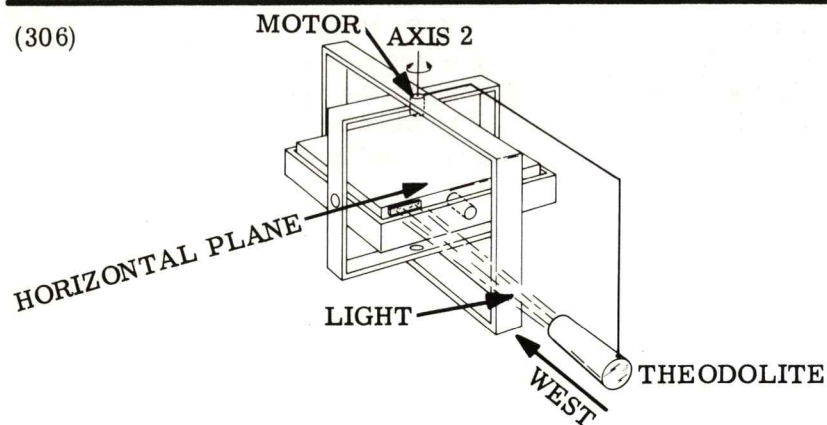
(305)



If the forward accelerometer was to be oriented north, the theodolite would shine its light:

- A. north.
- B. east.
- C. south.
- D. west.

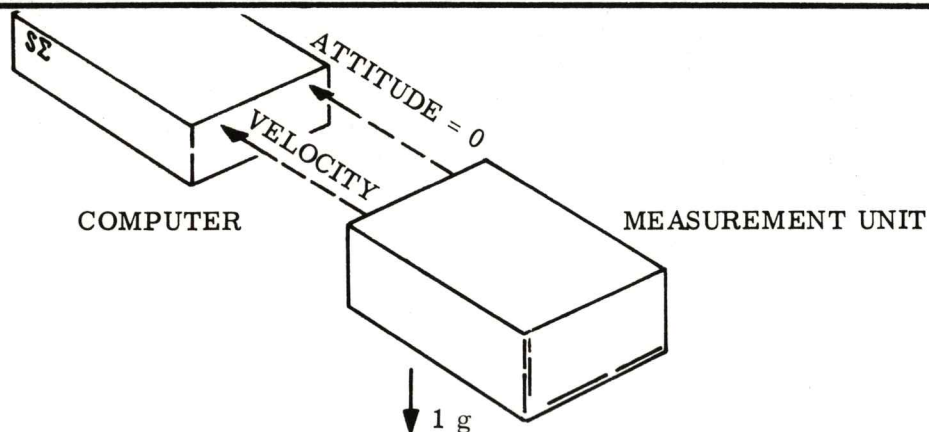
(306)



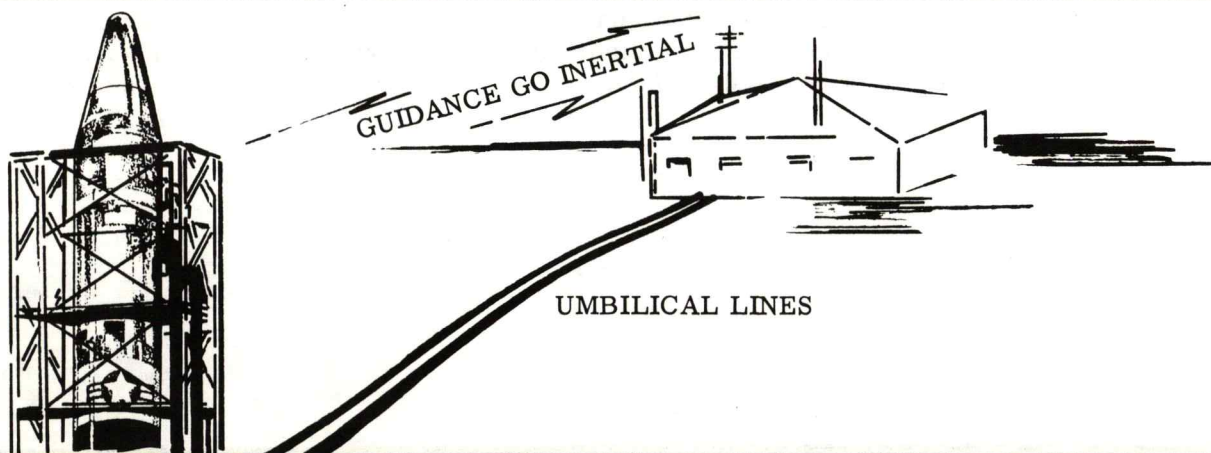
The stable member never goes out of the horizontal plane while it's searching for the theodolite.

- A. False
- B. True
- C. ---
- D. ---

(307)



(308)



TURN SELECTOR TO POSITION 11

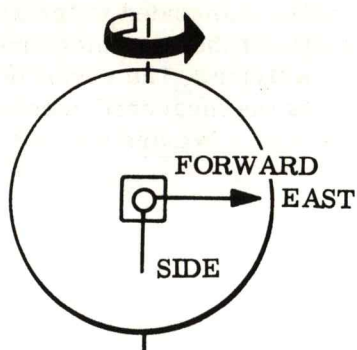
(309) Up until now our stable member has been held to an "earth referenced" position by the VSE and the theodolite. By earth referenced, we mean that as the earth turns the stable member turns with it always keeping itself in line with gravity and east. Out in space there is no east and there isn't much, if any, gravity. (There is a relative east in space, but for our purposes, the celestial sphere and associated coordinates would only serve to confuse, thus it will be covered in a later text to the depth it warrents.)

(310) When the command "guidance go inertial" is received, the VSE, theodolite and other compensations in the system are removed. The gyros are now in complete control of maintaining a stable reference. Any torque felt about the gyros input axis will result in an error signal. This error signal will be used to hold the stable member to its original pre-launch position as originally defined by the VSE and theodolite.

(311) We couldn't inertially reference the stable member earlier because the earth would then "rotate under the stable member" and our alignment would be useless. Think about this. If the stable member were inertially referenced (held stable with respect to space, not earth), then in six hours the UP accelerometer input axis would be pointing west and the forward accelerometer input axis would be pointing up.

(312) So, at T-4, the stable member is "inertially reference" so that the accelerometers are always going to remain in the same position with respect to space. No matter what the missile does, the stable member will never lose its original orientation.

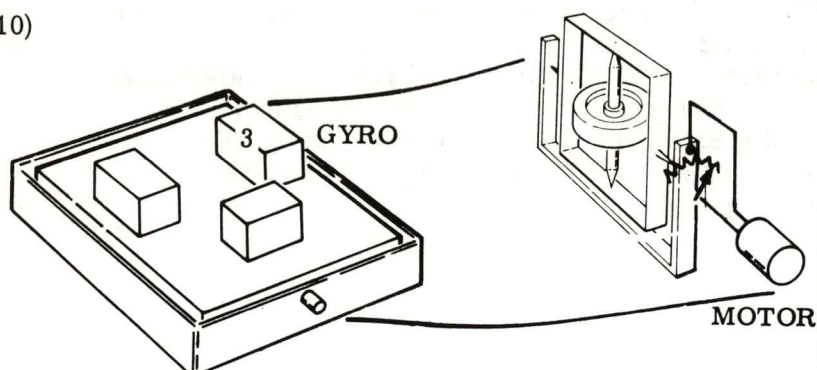
(309)



"Earth reference" implies that the axes of the stable member:

- A. move with respect to space.
- B. are stationary with respect to the earth.
- C. are fixed in space.
- D. A and B.

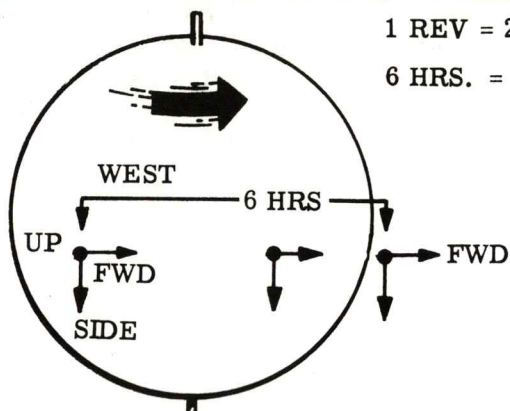
(310)



In order to hold the stable member earth referenced we used the:

- A. VSE and accelerometer.
- B. VSE and theodolite.
- C. gyros and theodolite.
- D. error from the computer.

(311)



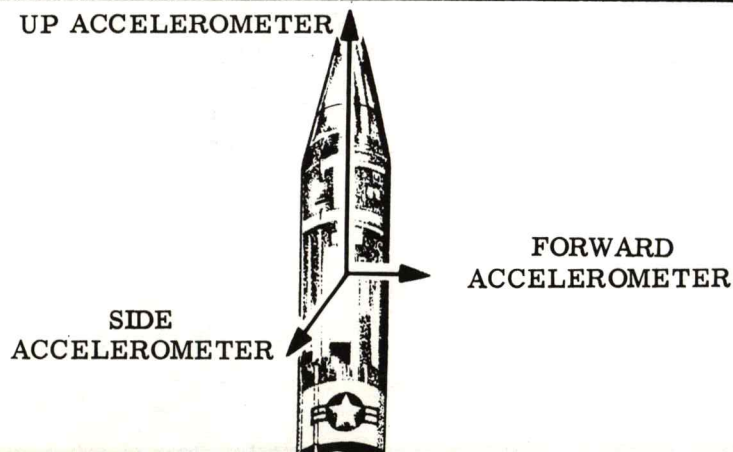
1 REV = 24 HRS.
6 HRS. = 1/4 REV.

If the stable member were inertially referenced for 12 hours, what direction would the forward accelerometer point?

- A. Up
- B. East
- C. West
- D. Down

(312)

UP ACCELEROMETER



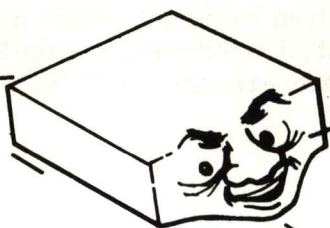
Inertially referenced implies that the accelerometer input axes are stable with respect to:

- A. space.
- B. the earth.
- C. the missile.
- D. the launch pad.

TURN SELECTOR TO POSITION 1

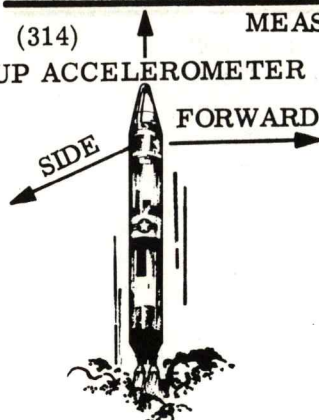
- (313) As soon as the inertial guidance/navigation system is commanded to terminate earth referencing compensations ("guidance go inertial") the computer proceeds to calculate velocity and distance. . . . it thinks it's flying. The result of the computers efforts are zero because after it subtracts the measured acceleration due to gravity, there isn't anything left to calculate with. We are still sitting on the launch pad.
-
- (314) Three -- two -- one -- ignition. . . . A short wait for the engines to build up the necessary thrust to lift our vehicle off the pad. "Lift off!" The sensors on the pad detect the weight of the missile being removed as it rises. The umbilicals which contained the wires for our earth referencing fall away. The computer is now receiving an increased number of counts from the "UP" accelerometer because the vehicle is being accelerated straight up. (Remember the accelerometers only sense an acceleration along their input axis.)
-
- (315) The computer accepts the accelerometer counts and calculates true velocity and distance. On the basis of this data, as compared to the ideal data, it will issue steering signals to the engines - but during the first part of the flight the steering signals will not be accepted by the flight control system (the flight control system changes the electrical output from the computer to hydraulic movement of the engines for steering).
-
- (316) The flight control system has some stabilizing gyros of its own that provide stabilizing control signals to the engines during the first seconds of flight. The sole purpose is to keep the missile pointed up, "balanced on its flames", similar to balancing a broom on the palm of your hand. (The flight control system is a separate system and is not part of the inertial guidance/navigation system.)

(313)

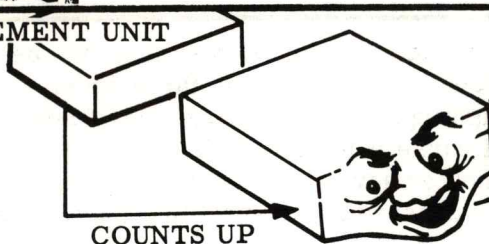


Can't fool me for long, I subtracted the acceleration due to gravity and found out I'm not moving yet.

(314)
UP ACCELEROMETER



MEASUREMENT UNIT



WOW! Here they come -- I'm goin' up!

(315)



MORE COUNTS

Come on you guys -- how about doing what I say!

NOT YET, GUIDANCE!

The flight control system is:

- A. the interface between the guidance computer and the engines.
- B. the interface between hydraulics and electrical schematics.
- C. A and D are correct.
- D. the "muscle power" for the computer commands.

(316)



A woman's work is never done. . . . housework and gyro demonstrations, yet!

The flight control system:

- A. uses a broom.
- B. C and D are correct.
- C. has gyros in it.
- D. is separate from the guidance/navigation system.

TURN SELECTOR TO POSITION 2

(317) After the computer has received sufficient counts from the "UP" accelerometer, it will send a signal to the flight control system telling it to give control of the vehicle to the inertial guidance/navigation system.

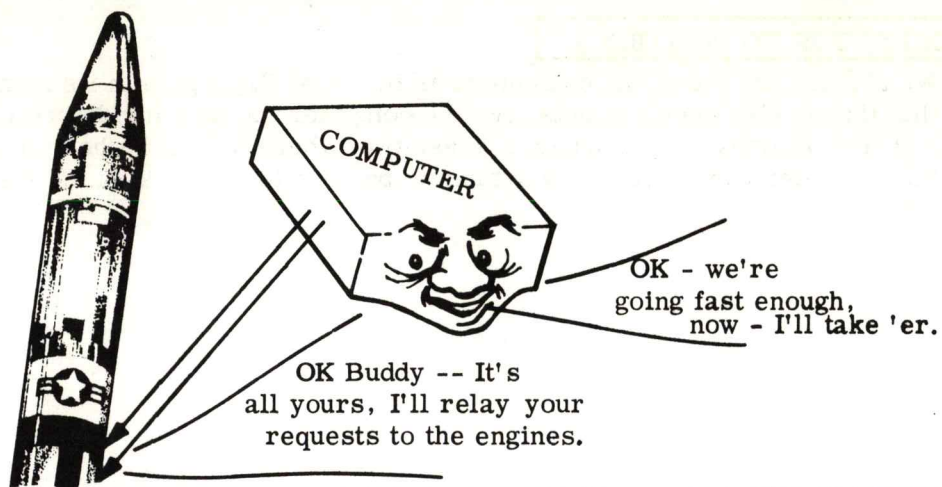
(318) All the time that the inertial guidance/navigation system has been "locked out", the computer has been receiving counts from the three accelerometers. The vehicle didn't really go straight up. Winds, changes in atmospheric conditions, and "throw out velocity" will cause it to deviate from a vertical ascent. The accelerometers kept the computer advised of any vehicle accelerations. The computer knows the vehicle's exact position, velocity and altitude.

(319) We mentioned the term "throw out velocity" so we had better explain it. With the missile sitting on the rotating earth, it is, and so are we, traveling at more than 950 miles per hour with respect to space. As soon as the missile leaves the earth, it has an easterly velocity equal to the velocity of that point on earth that it departed from. After the missile is launched, it encounters some atmospheric resistance (jet streams) to this easterly velocity. Any change in this velocity is measured by the accelerometers. (A change in velocity = acceleration.)

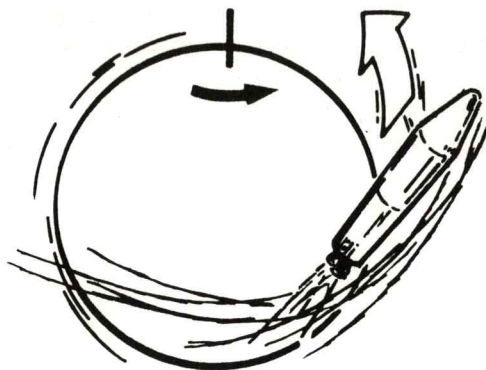
(320) Before any steering can be accomplished by the inertial guidance/navigation system, two things must be considered by the computer:

1. What velocity is needed (magnitude and direction).
2. Which way is the missile pointed.

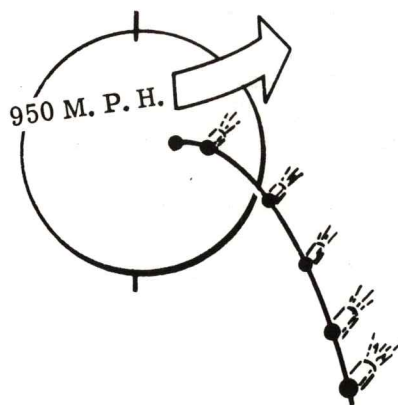
(317)



(318)



(319)



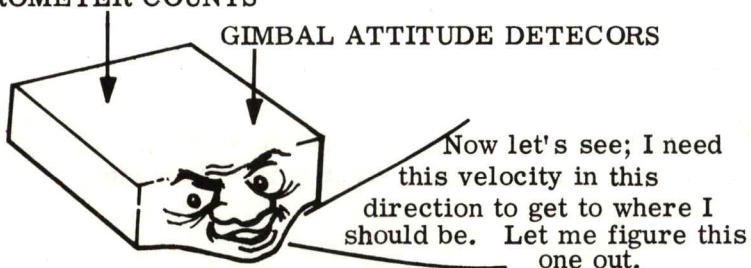
Accelerations caused by engine thrust along with accelerations due to ambient conditions must be measured by the accelerometers.

- A. True
- B. False
- C. ----
- D. ----

(320)

ACCELEROMETER COUNTS

GIMBAL ATTITUDE DETECORS



In order for the computer to issue steering commands it must know both magnitude and direction of the needed velocity.

- A. ----
- B. ----
- C. False
- D. True

TURN SELECTOR TO POSITION 3

(321) We already know that the computer has the ideal flight path in its memory and that the accelerometer counts give the computer the data for determining position and true velocity. By comparing these two (where it is and where it wants to go), the computer can determine what has to be done to get back on the ideal flight path.

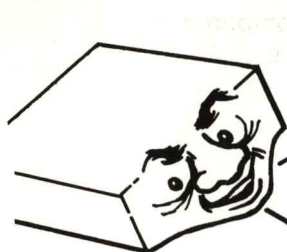
(322) In order to define missile attitude, the computer uses the gimbal attitude detectors that we discussed earlier. They were, prior to launch, on the center zero position. Recall that we said one volt out of these detectors indicated one degree of displacement so that if the vehicle was displaced from the original position by 10° , the computer would see 10 volts of gimbal angle error - advising it that there was a 10° displacement about a given gimbal axis.

(323) On the basis of these gimbal angle errors, the computer knows which way the nose of the missile is pointed and can move the engines to cause the missile to go "head first" to its destination. Don't assume that we want the gimbal angle error signals to be zero throughout the flight. They won't. They will probably all have an error voltage whose only purpose is to keep the computer advised, at all times, what the attitude of the missile is. For instance, if the missile was programed to do a turn, then the amount of turn is indicated by the gimbal angle error detectors. The computer could monitor the gimbal angle detectors and on the basis of their output stop turning the missile at the correct time.

(324) The mechanics of in flight information should be clear to you. Let's sum up the salient points covered thus far.

1. System erected using VSE and theodolite.
2. System inertially referenced and launched on time.
3. Flight control system "balanced" missile until sufficient "UP" velocity was achieved.
4. Computer has full control of missile and will guide missile on the basis of accelerometer counts, gimbal error detector outputs (attitude) and ideal flight profile.

(321)

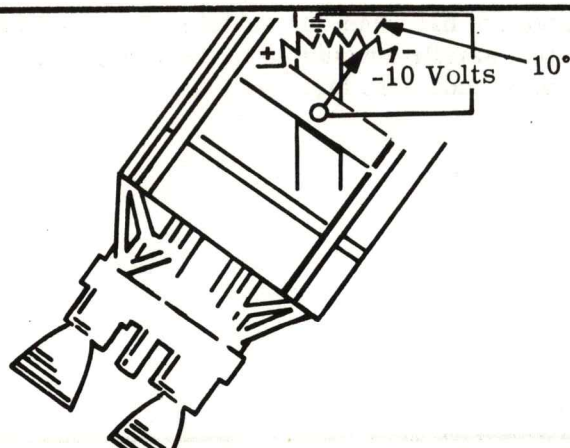
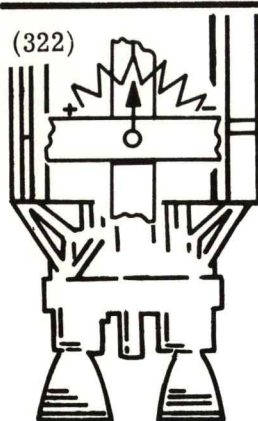


OK -- we need four more counts on the side accelerometer and two on the up accelerometer -- man -- this is NAVIGATION!!

The computer calculates the needed steering by comparing:

- A. time.
- B. fuel.
- C. actual acceleration to ideal acceleration.
- D. actual velocity and position to ideal velocity and position.

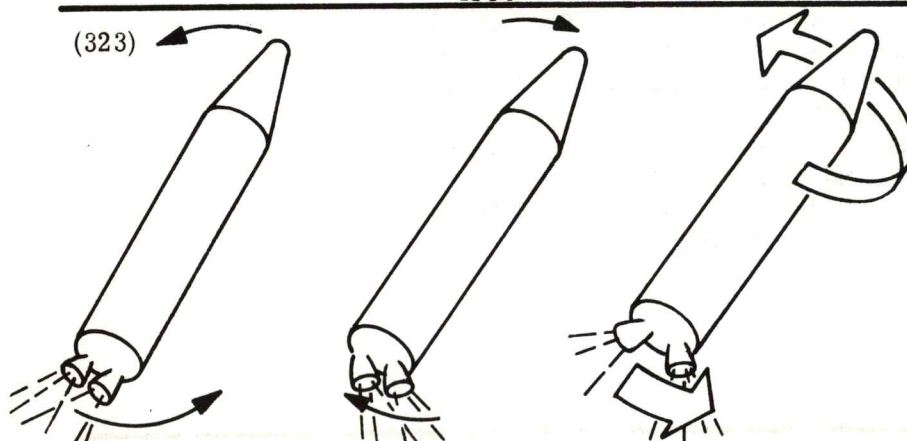
(322)



The gimbal attitude detectors give the computer information on:

- A. engine attitude.
- B. missile attitude.
- C. forward accelerometer attitude.
- D. A and C are correct.

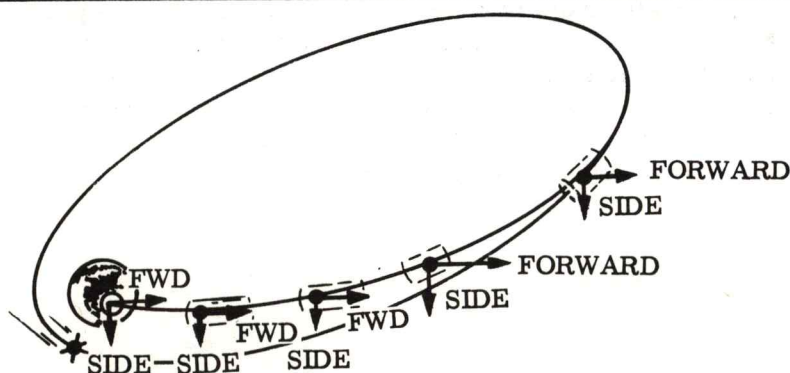
(323)



The only time that the gimbal attitude detectors will be "yawed" is:

- A. during lift off.
- B. at orbital injection.
- C. during steering.
- D. maybe just before inertially referencing the stable member.

(324)



TURN SELECTOR TO POSITION 4

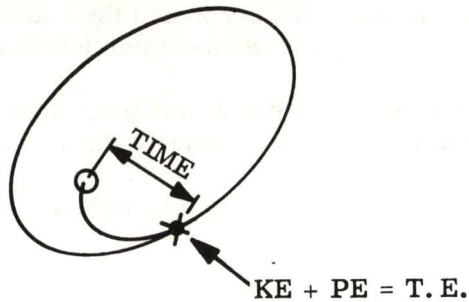
- (325) The computer has for its destination, and ours, a specific orbit at a specific time. From what we learned about orbits, we know that a specific orbit can be defined by the relationship of energies (KE and PE). For time, the computer will use a precision time generator located inside the computer which was started at the time the "guidance go inertial" command was issued.

-
- (326) The time of launch was correlated so that when our vehicle injects into the elliptical orbit the already orbiting satellite would be in the rendezvous position. Everything has gone on schedule so far.

-
- (327) We said earlier that kinetic energy is proportional to velocity² ($KE = 1/2 mv^2$) where m = mass of payload and v = tangential velocity of the payload in orbit. We also said that potential energy is inversely proportional to altitude (or distance) from the center of the earth. ($PE = -GMm/r$ where G is the universal gravitational constant, M = mass of the earth, m = mass of payload, and r = distance between center of earth and payload). We aren't interested in the mathematical analysis of the flight, only the relationship of velocity and distance with kinetic and potential energies respectively.

-
- (328) If we look at the accelerometer axes from space, we can see that the position of of these axes will allow the computer to determine altitude (acceleration x time = velocity, velocity x time = distance = altitude) and velocity. The predetermined velocity and altitude information is based upon the three dimensional system which defines a point in space. (The orthogonal set of three accelerometers define our coordinate system - they never move - do they?)

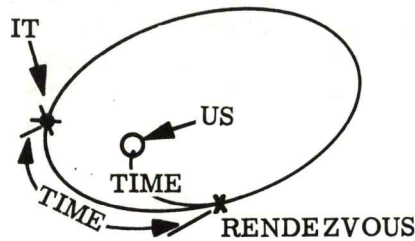
(325)



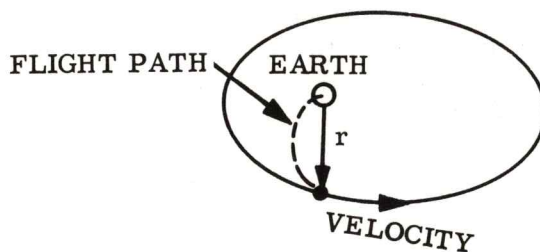
Time is generated:

- A. by the computer.
- B. by the flight control system.
- C. by the measurement unit.
- D. by an alarm clock in the engines.

(326)



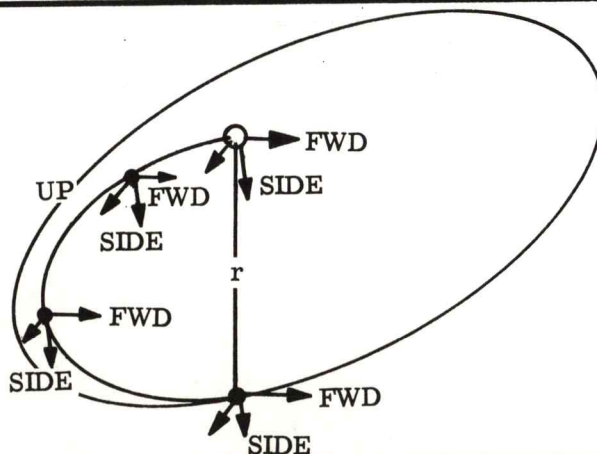
(327)



Kinetic energy is a function of _____ and potential energy is a function of _____.

- A. speed - velocity
- B. velocity - distance
- C. counts - gimbal angle
- D. none of the above.

(328)



The intersection of three perpendicular lines define:

- A. a target plane.
- B. a plane.
- C. a point.
- D. space.

TURN SELECTOR TO POSITION 5

- (329) Let's assume that at the point of orbital injection, the altitude is 100 miles and the orbital velocity at this point is 17,000 miles/hour. The position of the accelerometers are just like they were prior to launch (thanks to the gyros and their associated equipment). The total time required from launch to orbital injection is 12 minutes.

Let's use our accelerometer scale factor (4 ft/sec/count) and determine the acceleration count values that the computer is using to identify the orbital position.

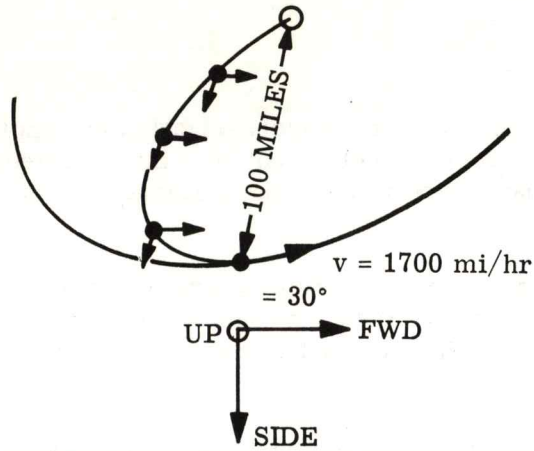
We will use the aforementioned values. They are only an approximation of the actual values but will suffice for our purposes.

-
- (330) The accelerometer scale factor of 4 ft/sec/count is equal to 2.73 mi/hr/count. This means that the "UP" accelerometer would have sent about 185 counts to the computer. The "forward" accelerometer will have sent 6230 counts to represent 17,000 mi/hr. The "side" accelerometer, in our case, would not have a net accumulation of counts if an orbital plane change were not introduced. Any deviation of the missile along the side accelerometers input axis would be an error and the computer would steer so that the counts from the side accelerometer would be reduced to zero.

-
- (331) As the vehicle approaches its destination, the actual accumulated values of accelerometer counts are approaching the ideal number of counts stored in the computer. The inertial guidance/navigation system has guided the vehicle so that all actual and ideal counts, from each accelerometer, compare favorably. At the instant that the difference between the actual and ideal accelerometer counts in the "UP", "forward" and "side" direction is zero, CUT OFF ENGINES. . . . WE ARE THERE.

-
- (332) Our timing was right, the orbit is correct, the vehicle performed well. The rendezvous has been accomplished.

(329)



The total number of counts associated with any of the three accelerometers is:

- A. a constant.
- B. all of these answers are correct.
- C. precalculated and inserted into the computer prior to flight.
- D. known before flight time.

(330)

average velocity for 100 mi. in 12 min.

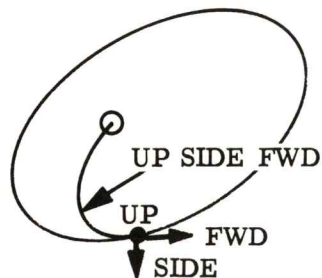
$$\frac{500 \text{ mi/hr}}{2.73 \text{ mi/hr}} = 185 \text{ counts (up)}$$

counts

$$\frac{17000 \text{ mi/hr}}{2.73 \text{ mi/hr}} = 6230 \text{ counts (forward)}$$

counts

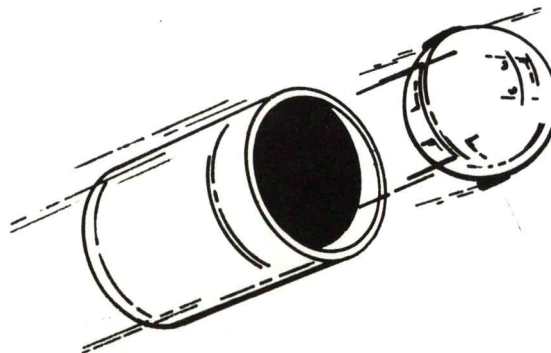
(331)



When the actual counts equal the ideal counts the total counts left to be gained is:

- A. maximum.
- B. minimum.
- C. questionable.
- D. zero.

(332)



(333) SUMMARY

This book has presented to you a basic over view of the mechanization and applications of inertial guidance/navigation systems. It is our belief that with this knowledge, and/or appreciation, of basic guidance and navigation you will be prepared to continue your studies in this area.

It should be clear to you that Newton's three laws of dynamics are the basis for all inertial guidance/navigation systems and that the theory of operation is very straight forward. The complexity arises in the fabrication and mechanization of Newton's laws.

Unique design, fabrication, assembly and test areas are required to produce a highly accurate and reliable inertial guidance/navigation system.

As you proceed through the remaining books in this course, you will learn to appreciate the simplicity of this book. The basic principles are always the same. The method of mechanizing basic principles will vary.

(333)

- END OF PROGRAMED PRESENTATION -

APPENDICES

I. REVIEW OF LINEAR QUANTITIES

TURN SELECTOR TO POSITION 1

- (1) In order that you may fully understand the concepts presented in this text, it may be necessary for you to review some of the basics of mechanics. This appendix contains a review of linear quantities. After completing this review, return to Frame 1 and proceed with the program. If you have trouble with the material later on, be sure to return and review this section.

(2) LINEAR QUANTITIES

The logical place to start this discussion is with the basic quantities. Basic quantities are quantities that cannot be broken down into more simplified quantities. There are three such basic quantities which are commonly used in gyro work. These are mass, distance and time. As you know, there are several measurement systems which can be used to define physical quantities. The system that is used almost exclusively in the gyro field is the metric system. Hence these basic quantities and any other quantities used in this text will be given in metric units. The three basic units are defined in the illustration.

-
- (3) Since there are only three basic quantities, any other quantities described in this book must be derived quantities, or quantities that can be broken down into simpler quantities. The first derived quantity to be presented will be "speed". Speed is defined as the time rate of change of distance, or:

$$\text{Speed} = \frac{\Delta s \text{ (change of distance)}}{\Delta t \text{ (change of time)}}$$

A common illustration of the concept of speed is the speedometer on your automobile. This meter gives you a constant indication of the rate at which you are changing distance (changing your position) with respect to time. It follows that the dimensions of speed will be centimeter per second ($\frac{\text{cm}}{\text{sec}}$) or some other dimension of distance and time.

-
- (4) There is often confusion between the term speed, and the term velocity. In fact the terms are often incorrectly used interchangeably. The difference, and this is important, is that speed is a scaler quantity (possesses only magnitude) and velocity (v) is a vector quantity (possesses both magnitude and direction). However, since speed is always in some direction, the term velocity is usually used. Thus velocity can also be defined as the time rate of change of distance or:

$$v = \frac{\Delta s \text{ (change of distance)}}{\Delta t \text{ (change of time)}}$$

(1)



- (2) MASS (m) - The quantity of material or matter in a body, measured in GRAMS.

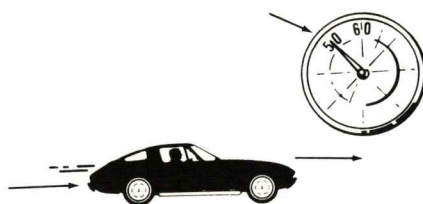
DISTANCE (s) - Length, measured in CENTIMETERS.

TIME (t) - Interval, measured in SECONDS.

The three basic quantities are mass, distance, and time. These quantities are measured in:

- A. grams, centimeters and seconds.
- B. grams, kilograms and centigrams.
- C. seconds, minutes and hours.
- D. centimeters, meters and kilometers.

(3)



When the speedometer remains at 50 m.p.h., you are traveling at a constant speed.

Speed is:

- A. change of acceleration with respect to time.
- B. change of speed with respect to time.
- C. change of position with respect to time.
- D. none of the above.

- (4) A sample problem should help crystalize this concept.

A slowly moving shuffleboard puck travels 300 centimeters in 5 seconds. What is its average velocity?

$$v = \frac{s}{t} \quad v = \frac{300 \text{ centimeters}}{5 \text{ seconds}}$$

or $v = 60 \text{ cm/sec.}$

A block of wood is moving across a surface at a constant rate. In 3 seconds it covers a distance of 12 centimeters; therefore, its velocity is:

- A. 2 cm/sec.
- B. 5 cm/sec.
- C. 4 cm/sec.
- D. 3 cm/sec.

TURN SELECTOR TO POSITION 2

- (5) Notice that the velocity equation ($v = \frac{s}{t}$) can be manipulated to yield distance by multiplying both sides of this equation by time

$$(t) v = \frac{s}{t} (t) \quad \therefore s = vt$$

-
- (6) Now that the concept of velocity is clear, the derived quantity acceleration can be discussed. Acceleration is the time rate of change of velocity or acceleration = Δ velocity \div Δ time. The automobile illustration is again applicable. If you are traveling in an automobile at the constant velocity of 40 miles per hour, and you decide that you wish to increase your velocity to 60 miles per hour, then you depress the foot pedal and accelerate the automobile. In effect, you change your velocity with respect to time. It is evident that the dimension of acceleration is distance per time period - per time period or centimeters per second per second (cm/sec/sec).

-
- (7) Very often, the dimension of acceleration is written as cm/sec². This is only a convenient way to state cm/sec/sec so don't be confused by this point. Remember acceleration is the time rate of change of velocity or:

$$\frac{\text{cm/sec}}{\text{sec.}}$$

-
- (8) Notice that a decrease in velocity with respect to time fulfills all the requirements of the acceleration equation; i. e., $a = \frac{\Delta v}{\Delta t}$. This decrease in velocity with respect to time is called deceleration, and has all the characteristics of acceleration. Deceleration, then, can be thought of as a negative acceleration.

- (5) Using the shuffleboard puck example, let's solve for distance if we are given only velocity (60 cm/sec) and time (5 seconds).

$$s = vt$$

$$s = 60 \text{ cm/sec} \cdot 5 \text{ sec}$$

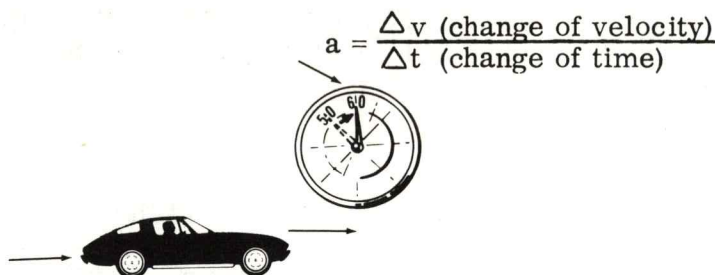
$$s = 300 \text{ cm}$$

and our answer checks out.

If a block of wood is moving across a surface at a velocity of 4 cm/sec, what distance will it cover in 3 seconds?

- A. 12 cm/sec
- B. 12 cm
- C. 4 cm
- D. 4 cm/sec

(6)



This automobile is in the process of increasing its velocity from 50 miles per hour to 60 miles per hour, or it is accelerating.

Acceleration is defined as:

- A. time rate of change of distance.
- B. vt
- C. time rate of change of velocity.
- D. $\frac{s}{t}$

(7)

A sample problem may help to illustrate acceleration.

Let's return to the shuffleboard puck. You'll recall that when we left it, it was traveling at the constant velocity of 60 cm/sec. Now suppose that for some reason (we will discuss this reason shortly) the velocity of the puck increased to 100 cm/sec in the time interval of 10 sec. It is evident that the puck was accelerated, and to find the magnitude of this acceleration we merely solve the basic equation:

$$a = \frac{\Delta v}{\Delta t} = \frac{|\text{final } v - \text{initial } v|}{\text{time interval of change}}$$

$$a = \frac{100 \text{ cm/sec} - 60 \text{ cm/sec}}{10 \text{ sec}} = \frac{40 \text{ cm/sec}}{10 \text{ sec}} = \frac{4 \text{ cm/sec}}{\text{sec}}$$

A body is observed falling at a velocity of 1960 cm/sec. 3 seconds later this same body is observed to be falling at 4900 cm/sec. What is the acceleration of this body?

- A. 980 cm/sec²
- B. 1000 cm/sec²
- C. 900 cm/sec²
- D. 960 cm/sec²

(8)

Let's apply acceleration to the shuffleboard puck, and observe its behavior. When we left it, it had a velocity of 100 cm/sec. Suppose for some reason the puck slows down to 60 cm/sec. Only this time it takes 5 sec. By applying the acceleration equation, the magnitude of this acceleration can be found.

$$a = \frac{\Delta v}{\Delta t} = \frac{|\text{final } v - \text{initial } v|}{\text{time interval of change}}$$

$$a = \frac{60 \text{ ft/sec} - 100 \text{ ft/sec}}{5 \text{ sec}} = \frac{40 \text{ ft/sec}}{5 \text{ sec}} = \frac{8 \text{ ft/sec}}{\text{sec}}$$

The acceleration of the puck is: $\frac{8 \text{ ft/sec}}{\text{sec}}$

An automobile slows down from 60 miles/hour to 30 miles/hour in an elapsed time of 11 seconds. What is the acceleration of the automobile?

- A. 6 ft/sec
- B. 4 mi/hr
- C. 6 mi/hr
- D. 4 ft/sec

TURN SELECTOR TO POSITION 3

- (9) As the velocity equation could be manipulated to yield distance in Frame 5, we shall see that the acceleration equation can be manipulated to yield velocity. This is done by solving the equation $a = \frac{\Delta v}{\Delta t}$ for Δv . Then

$$\Delta v = a \Delta t$$

A sample problem which illustrates the interrelationship between acceleration and velocity is shown to the right, and it should help to explain the point being made.

-
- (10) Distance can also be determined from the acceleration term. This relationship is a little more subtle than the other relationships we have shown, but it can be easily seen from the following derivation:

$$s \text{ (distance)} = v \text{ (velocity)} \times t \text{ (time)}$$

When we are considering an acceleration, we must take into account the fact that velocity is changing with respect to time, thus, we must find the average velocity for the above equation. In this case (for simplicity) we must assume that the initial velocity before an acceleration occurred was 0 (body is at rest), and that the acceleration of the body was constant. Then, to find the average velocity for the above equation, we merely divide the final velocity of the body by 2.

$$v \text{ ave} = \frac{vf}{2}$$

Substituting this into the above equation:

$$s = \frac{vf}{2} t$$

But we know that $v = a t$ so by substituting:

$$s = \frac{at}{2} \cdot t$$

or

$$s = \frac{1}{2} a t^2$$

A sample problem which illustrates the interrelationship between acceleration and distance is shown to the right, and it should help to explain the point being made.

- (9) Find the change of velocity of a body that has been subjected to an acceleration of 10 ft/sec^2 for a time interval of 10 seconds.

$$\Delta v = a \Delta t$$

$$\Delta v = \frac{10 \text{ ft/sec}}{\text{sec}} \cdot 10 \text{ sec}$$

$$\Delta v = 100 \text{ ft/sec}$$

Velocity can be defined as:

- A. distance divided by time.
- B. acceleration times time.
- C. none of these.
- D. A and B above.

-
- (10) Find the total distance covered by a body that has been subjected to an acceleration of 10 ft/sec^2 for a time interval of 10 seconds. Assume that the body starts from rest.

$$s = \frac{1}{2} a t^2$$

$$s = \frac{1}{2} \cdot \frac{10 \text{ ft/sec}}{\text{sec}} \cdot (10 \text{ sec})^2$$

$$s = \frac{1}{2} \cdot \frac{10 \text{ ft/sec}}{\text{sec}} \cdot 100 \text{ sec}^2$$

$$s = 500 \text{ ft}$$

If you are given the initial velocity, acceleration and time interval of acceleration of a body, you can determine:

- A. distance covered.
- B. A and C.
- C. body velocity
- D. none of the above.

TURN SELECTOR TO POSITION 4

- (11) In the previous frames we discussed acceleration without any mention of how the acceleration was brought about. Acceleration is always produced by the derived quantity "force", and this force must be unbalanced. The relationship of force, mass and acceleration are shown below:

$$a = \frac{F}{m}$$

where; a is acceleration, m is mass (remember, it is a basic quantity), and F is force.

Don't let the term unbalanced force bother you, it will be discussed shortly.

-
- (12) In the last frame it was shown that acceleration always resulted from application of an unbalanced force. However, it does not necessarily follow that every applied force will produce an acceleration. For example, a book resting on your desk top is subjected to a force (gravity) which is tending to accelerate the book toward the center of the earth. However, the book is stationary because the desk top is exerting an equal and opposite force on the book. Hence, we can now define force as a push or pull exerted on an object. This force will produce an acceleration, only if it is not offset by an equal and opposite force (i.e., the force must be unbalanced).

-
- (13) Let's see if we can assign a dimension to this push or pull exerted upon a body. By manipulating the equation $(a = \frac{F}{m})$ which was given in frame 12, it can be shown that force equals the product of the mass of the body being accelerated, and the rate of acceleration, or $F = m a$. You recall that mass is given in grams and acceleration in cm/sec/sec, thus the product of the two is given in gm - cm/sec/sec (read gram centimeters per second per second). This is rather lengthy terminology so it has been shortened to the term "dyne". The dimension of force then, is a "dyne", which is one gm - cm/sec/sec.

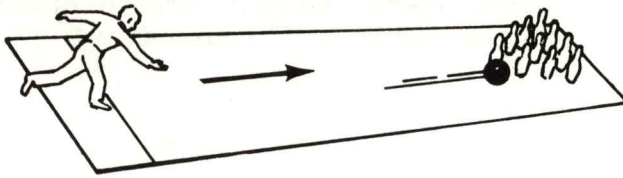
-
- (14) In the case of the book on your desk, a magnitude can also be assigned to the force that it exerts on the desk top. Assume that the book has a mass of 1000 gms and that the acceleration of gravity is 980 cm/sec/sec. Substituting in the equation:

$$F = m a$$

$$F = 1000 \text{ gm} \times \frac{980 \text{ cm/sec}}{\text{sec}} = 980,000 \text{ dynes}$$

Thus the book is exerting a force on the desk top of 980,000 grams. But, since the book is not accelerating toward the center of the earth, it is evident that the desk is pushing up with a force equal and opposite to the downward force of the book, or 980,000 dynes upward.

- (11) This man has accelerated the bowling ball.

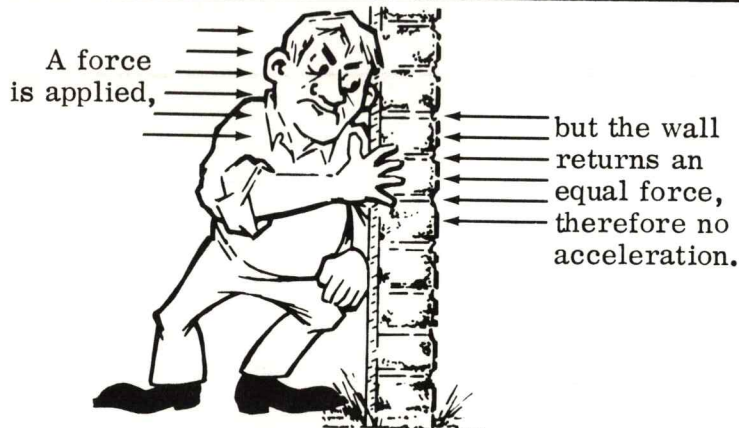


Acceleration is always a result of an unbalanced force.

An unbalanced force acting on a body will always cause a:

- A. time rate of change of velocity.
- B. time rate of change of acceleration.
- C. torque.
- D. all of the above.

- (12)



Force is best defined as:

- A. the cause of a time rate of change of velocity.
- B. the cause of acceleration.
- C. a push or pull exerted on a body.
- D. all of the above.

- (13) A sample problem will help illustrate the dimension of force.

A body with a mass of 10 grams is accelerating at a rate of 20 cm/sec/sec. What is the magnitude of the unbalance force acting on this body?

$$F = ma \quad F = 10 \text{ gm} \times 20 \text{ cm/sec/sec}$$

$$F = \frac{200 \text{ gm-cm/sec}}{\text{sec}}$$

$$F = 200 \text{ dynes}$$

A force of 300 dynes is applied to a body and the result is an acceleration of 75 cm/sec/sec. What is the mass of this body?

- A. 1/4 gm
- B. 4 gm
- C. 40 gm
- D. 40 dynes

- (14) Now you try one.

A free mass of 200 grams is acted upon by a force of 500 dynes. What is the resulting acceleration?

$$\text{Answer: } 2\frac{1}{2} \text{ cm/sec}^2$$

A brick is observed to be at rest on the ground. If the mass of the brick is equal to 3000 grams, what force is the ground exerting up on the brick?

- A. 294,000 dynes
- B. 29,400 dynes
- C. 2,940,000 dynes
- D. 29,400,000 dynes

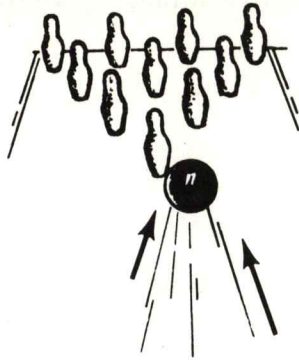
HINT-the acceleration of gravity is 980 cm/sec/sec.

TURN SELECTOR TO POSITION 5

- (15) One other term, similar to force, that should be understood is the derived quantity "momentum". Momentum is the quantity of motion possessed by a body; i.e., a body in motion tends to stay in motion unless, as we know, it is acted upon by an unbalanced force. The quantity of momentum is determined by the product of the mass and its velocity ($M = m v$), and the dimension given to this product is gm - cm/sec.

SPACE FOR ADDITIONAL NOTES:

- (15) Bowling ball continues to roll after it is released because of its momentum.



$$M = mv$$

Momentum is equal to the product of:

- A. the mass of an object times its acceleration.
- B. the mass of an object times its velocity.
- C. the force of an object times its acceleration.
- D. the length of an object times its velocity.

TURN SELECTOR TO POSITION 6

(16) REVIEW OF LINEAR QUANTITIES

Before leaving this area of linear quantities, let's stop a minute to review what we have covered.

1. There are only three basic quantities in the field of mechanics. These are:
 - a. mass - m - measured in grams
 - b. distance - s - measured in centimeters
 - c. time - t - measured in seconds.
2. All other quantities are derived quantities, or quantities that can be reduced to more simplified quantities. Thus far we have discussed five derived quantities. These are:
 - a. speed - change of distance with respect to time. This term is seldom used since it is a scalar quantity (represents only magnitude - not direction) - measured in centimeters per second.
 - b. velocity - v - This is the same as speed only it is a vector quantity (represents both magnitude and direction) - measured in cm/sec.
 - c. acceleration - a - change of velocity with respect to time - measured in cm/sec/sec.
 - d. force - F - a push or a pull exerted on a body - measured in dynes.
 - e. momentum - M - the quantity of motion possessed by a body - measured in gm - cm/sec.
3. The interrelationships among the quantities above are given here in equation form. You should be familiar with these now.

a. speed or velocity - $v = \frac{\Delta s \text{ (change of distance)}}{\Delta t \text{ (change of time)}}$

b. change of distance - $\Delta s = v \cdot \Delta t$

c. acceleration - $a = \frac{\Delta v}{\Delta t}$

d. change of velocity - $\Delta v = a \cdot \Delta t$

e. change of distance - $\Delta s = 1/2 a \cdot \Delta t^2$

f. force - $F = m a$

g. acceleration - $a = \frac{F}{m}$

h. mass - $m = \frac{F}{a}$

i. momentum - $M = m v$

j. mass - $m = \frac{M}{v}$

k. velocity - $v = \frac{M}{m}$

- (16) Match the letter of the descriptive phrase on the right with its corresponding term on the left.

Force	_____	a. prime quantity-interval-measured in seconds.
Mass	_____	b. prime quantity-mass-measured in grams.
Speed	_____	c. prime quantity-length-measured in centimeters.
Velocity	_____	d. derived quantity-scalar-time rate of change of distance.
Momentum	_____	e. derived quantity-vector-time rate of change of distance.
Distance	_____	f. derived quantity-vector-time rate of change of velocity.
Acceleration	_____	g. derived quantity-a push or pull exerted on a body.
Time	_____	h. derived quantity-quantity of motion possessed by a body.

Speed is defined as the:

- A. time rate of change of velocity.
- B. time rate of change of distance-vector.
- C. time rate of change of distance-scalar.
- D. prime quantity.

Velocity is defined as the:

- A. time rate of change of distance - scalar.
- B. prime quantity.
- C. time rate of change of velocity.
- D. time rate of change of distance - vector.

Acceleration is defined as the:

- A. time rate of change of velocity.
- B. time rate of change of distance - scalar.
- C. time rate of change of distance - vector
- D. prime quantity.

ANSWERS:

Force	- g	Momentum	- h
Mass	- b	Distance	- c
Speed	- d	Acceleration	- f
Velocity	- e	Time	- a

Force is defined as:

- A. the quantity of motion possessed by a body.
- B. a prime quantity.
- C. a push or pull exerted on a body.
- D. a couple of torques.

II. SAMPLE TEST

ACceler-aide Test INERTIAL INSTRUMENT SERIES

This particular test has been written to cover material presented in the programed instruction text entitled:

"INTRODUCTION TO GUIDANCE/NAVIGATION"

This test is designed to be performed by you with no notes or reference material. You should complete the test within a 30 minute time period.

PART I. TRUE - FALSE STATEMENTS (2 Points Each) Circle the "T" or "F" for True or False, respectively.

- | | | | |
|---|---|-----|---|
| T | F | 1. | Basic inertial guidance/navigation is based on the mechanization of Newton's fourth law of dynamics. |
| T | F | 2. | $F = MA$. This is an expression of one of Newton's laws where F = force resulting from an A = acceleration of a given mass = M . |
| T | F | 3. | When discussing basic gyro theory a good phrase to remember is "out into spin" because this will help you to determine the positive input axis. |
| T | F | 4. | The fact that one can steer a bicycle by simply leaning in the direction of the desired turn is a good example of precession. |
| T | F | 5. | The accelerometer discussed in this book used gyroscopic precession to indicate a force due to acceleration. |
| T | F | 6. | The units of the accelerometer scale factor is ft/sec/count. |
| T | F | 7. | The counts sent to the computer are a measure of distance. |
| T | F | 8. | Gimbals are used to isolate the stable member from vehicle movement. |
| T | F | 9. | Gyros are used to measure velocity. |
| T | F | 10. | Accelerometers are used to stabilize the stable member. |
| T | F | 11. | Orbits are basically determined by the magnitude of the total energy (TE) in the system. |
| T | F | 12. | For a circular or elliptical orbit the total energy of the system must be negative. |
| T | F | 13. | Potential energy is directly related to velocity. |
| T | F | 14. | Two types of inertial guidance are implicit and explicit. |

- T F 14. Explicit guidance confers that the vehicle will be guided along an ideal flight path.

PART II. MULTIPLE CHOICE STATEMENTS (2 Points Each)

Circle the letter corresponding to the most correct answer or statement.

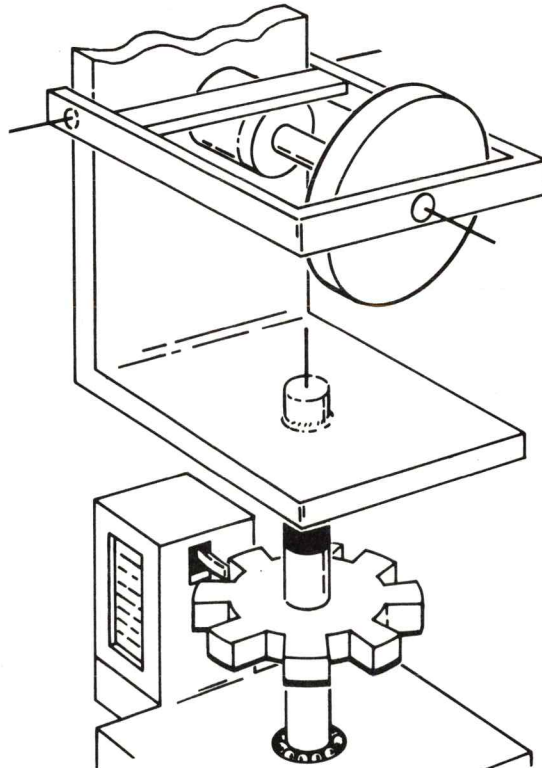
1. The stable member is held stable by:
 - a. the computer using data from the gyros.
 - b. the accelerometer outputs being routed to gimbal torque motors.
 - c. the gimbal torque motors which derive their input from the gyros.
 - d. frictionless gyros using the computer counts.
2. The sole purpose of the stable member is to:
 - a. provide a purpose for the gimbals.
 - b. keep two orthogonal.
 - c. provide a measurement reference.
 - d. keep the VSE vertical.
3. The definition of navigation as used in this text is:
 - a. the ability to go from one point to another point with no outside command information.
 - b. the ability of determining position.
 - c. the ability to guide.
 - d. none of the above answers are correct.
4. In order to perform an inertial guidance/navigation function it is necessary to know:
 - a. where you start and where you want to go.
 - b. time enroute.
 - c. velocity, attitude and computer readout.
 - d. could be "a" or "a" and "b".
5. In addition to knowing geographical location of the start point, a predeparture orientation of the stable member is necessary. To accomplish this orientation it is necessary to:
 - a. establish a horizontal and vertical plane.
 - b. establish gravity and horizontal.
 - c. establish a horizontal plane and the direction of local gravity.
 - d. none of the above are correct.
6. To inject a payload into a circular orbit the energy relationships are:
 - a. KE much less than PE.
 - b. total energy is positive.
 - c. KE is equal to $PE/2$.
 - d. PE is equal to $KE/2$.

7. The accelerometers are placed on the stable member with their input axes orthogonal (mutually perpendicular) because:
 - a. this is the only way they fit.
 - b. this provides sensing ability in any possible direction.
 - c. the gyros dictate this positioning because they are orthogonal also.
 - d. b and c.
8. The two steps required to align the stable member to a known earth orientation are:
 - a. VSE and gyro compassing.
 - b. establish a horizontal plane and establish a line in that plane.
 - c. establish a horizontal plane and a vertical plane using the necessary devices.
 - d. use a VSE to establish azimuth and a theodolite to establish heading.
9. A system is said to be inertially (space) referenced when:
 - a. earth rate compensations are introduced via the computer.
 - b. the accelerometers are fixed with respect to the earth.
 - c. the stable member is fixed with respect to the vehicle motion.
 - d. the stable member is fixed with respect to space.
10. An aircraft flying over the earth is following a Rhumb line route. The aircraft is:
 - a. taking the least distance route.
 - b. keeping a constant magnetic heading.
 - c. crossing the great circle route with minimum energy.
 - d. making a mistake.
11. The stable member associated with the measurement unit in an aircraft will be:
 - a. inertially referenced.
 - b. earth referenced.
 - c. compensated for local gravity vector by torquing the stable member.
 - d. certainly not "a".
12. The potential energy associated with a satellite orbit is an inverse function of the distance measured from:
 - a. the earth to the center of the satellite.
 - b. the center of the satellite to the mean distance at apogee.
 - c. the center of the earth to the center of the orbit.
 - d. the center of the earth to the center of the satellite.
13. The velocity associated with the satellite's kinetic energy is:
 - a. velocity which is tangent to the orbit at a given time.
 - b. the relative velocity of the earth with respect to the instantaneous satellite positional velocity.
 - c. the speed of the orbit.
 - d. the velocity of the orbit.

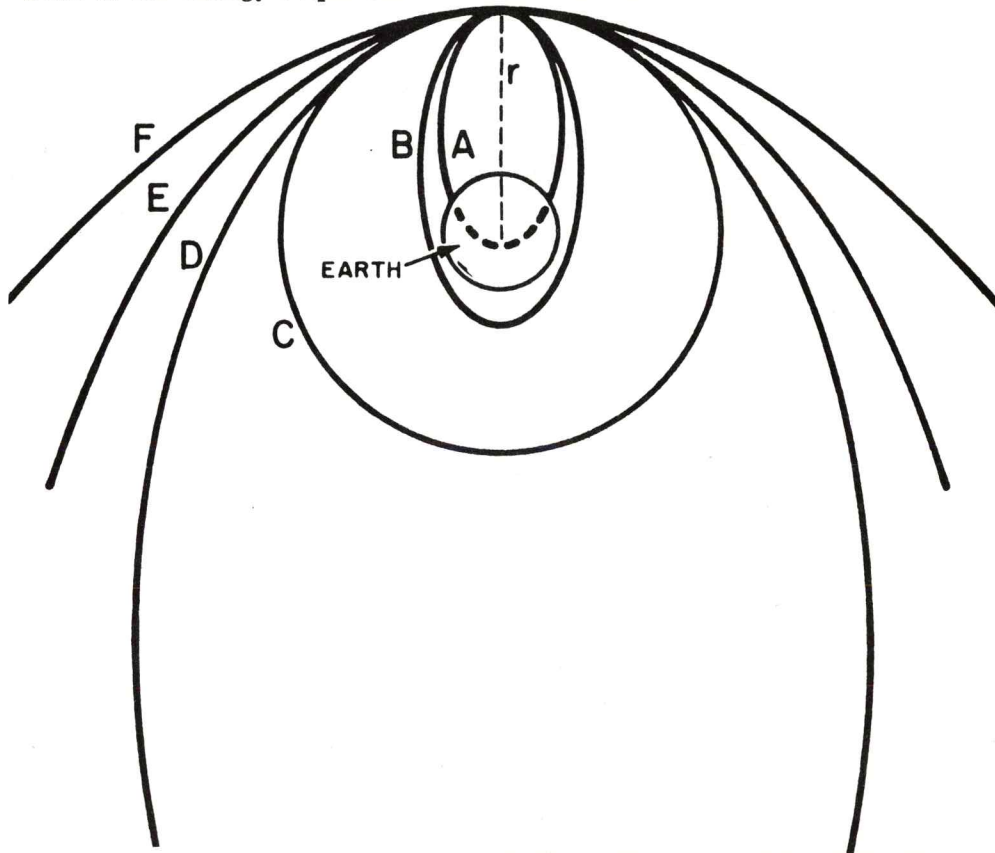
14. In an elliptical orbit, the application of Kepler's equal area law indicates that the satellite will be:
- a. going faster at apogee than at perigee.
 - b. going faster at perigee than at apogee.
 - c. going at equal speeds when the orbit intersects the minor axis.
 - d. both b and c.
15. The attitude of the vehicle was needed because:
- a. we certainly don't want a grouchy missile.
 - b. the computer needed a missile direction so it could steer the correct way.
 - c. the accelerometers give only vehicle velocity and couldn't detect missile attitude.
 - d. both b and c.
16. Lines of latitude are:
- a. scribed through the poles of the earth.
 - b. scribed parallel to the equator.
 - c. are really great circle routes.
 - d. a and c.
17. The theodolite used in the system erection prior to launch:
- a. defined azimuth.
 - b. had a light source only.
 - c. was made in Japan.
 - d. was a gravity reference.
18. The computer knew when the vehicle was in the correct orbit by:
- a. comparing the actual number of accelerometer counts to the ideal number of accelerometer counts.
 - b. comparing the gyro outputs to the accelerometer outputs.
 - c. comparing its position with the measurement units position.
 - d. comparing its position to the position of the payload.
19. The computer requires a time reference because:
- a. it must calculate true velocity and distance which are based on time.
 - b. it must know total flying time.
 - c. it must wake up the astronaut.
 - d. a and b.
20. The sensors of the VSE had to be aligned with the gimbal axes because:
- a. that's the way it is.
 - b. this identified which gimbal had to turn to make any out of level correction.
 - c. during flight the VSE had to route signals to the appropriate gimbal torque motor.
 - d. b and c.

PART III. PROBLEMS (10 Points Each)

1. Explain how the accelerometer operates and how its scale factor was determined.



2. What is the energy requirements for orbits A, B, C, D, E and F?



3. Explain the parts of the measurement unit. Give the purpose of each.

SAMPLE TEST - ANSWERS

PART I. TRUE - FALSE

- | | | | |
|----|---|-----|---|
| 1. | F | 9. | F |
| 2. | T | 10. | F |
| 3. | F | 11. | T |
| 4. | T | 12. | T |
| 5. | T | 13. | F |
| 6. | T | 14. | T |
| 7. | F | 15. | T |
| 8. | T | | |

PART II. MULTIPLE CHOICE

1. c. the gimbal torque motors which derive their input from the gyros.
2. c. provide a measurement reference.
3. b. the ability of determining position.
4. d. could be "a" or "a" and "b".
5. d. none of the above are correct.
6. c. KE is equal to $PE/2$.
7. b. this provides sensing ability in any possible direction.
8. b. establish a horizontal plane and establish a line in that plane.
9. d. the stable member is fixed with respect to space.
10. b. keeping a constant magnetic heading.
11. d. certainly not a.
12. d. the center of the earth to the center of the satellite.
13. a. velocity which is tangent to the orbit at a given time.
14. d. both b and c.
15. d. both b and c.
16. b. scribed parallel to the equator.
17. a. defined azimuth.
18. a. comparing the actual number of accelerometer counts to the ideal number of accelerometer counts.
19. d. a and b.
20. b. this identified which gimbal had to turn to make any out of level correction.

PART III. PROBLEMS

1. Reference frames 100 through 121
2. Reference frames 168 through 174
3. Reference frames 122 through 124

INTRODUCTION TO GUIDANCE/NAVIGATION

Answer Sheet

1. ----

2. ----

3. ----

4. ----

5. ----

6. A. force
C. third

7. B. second

8. ----

9. ----

10. A. are self-contained.

11. D. one known point to another
known point.
B. acceleration.

12. ----

13. ----

14. A. one axis.

15. ----

16. ----

17. ----

18. ----

19. C. direction

20. ----

21. ----

22. ----

23. ----

24. A. direction
25. ----

26. ----

27. A. two directional distances.

28. ----

29. ----

30. D. both A and B are correct.

31. C computer.

32. ----

33. A. force equals mass times
acceleration.
D. positive input axis.
B. velocity and distance.
A. stabilization system.

34. ----

35. ----

36. D. spin axis.

37. D. the positive end of the spin axis.

38. ----

39. B. mutually perpendicular.

40. C. perpendicular to the plane
containing the input axis.

41. ----

42. ----

43. ----

44. C. precession.

45. ----

46. ----

47. ----

- | | | | | |
|-----|------|--|------|-----------------------------|
| 48. | A. | gimbal. | 73. | ---- |
| 49. | D. | mutually perpendicular to the spin axis and output axis. | 74. | ---- |
| 50. | ---- | | 75. | ---- |
| 51. | ---- | | 76. | ---- |
| 52. | ---- | | 77. | ---- |
| 53. | ---- | | 78. | ---- |
| 54. | ---- | | 79. | B. False |
| 55. | C. | all of these answers are correct. | 80. | ---- |
| 56. | B. | gimbal. | 81. | C. attitude |
| 57. | ---- | | 82. | A. magnitude - direction |
| 58. | ---- | | 83. | C. gimbal movement. |
| 59. | ---- | | 84. | ---- |
| 60. | ---- | | 85. | ---- |
| 61. | A. | its input axis. | 86. | ---- |
| 62. | ---- | | 87. | ---- |
| 63. | ---- | | 88. | ---- |
| 64. | C. | the stable member. | 89. | A. 32.2 ft/sec^2 |
| 65. | D. | 90° | 90. | ---- |
| 66. | D. | one gyro or a combination of gyros. | 91. | D. directly |
| 67. | C. | one | 92. | A. mass and acceleration. |
| 68. | A. | rotational input. | 93. | C. 300 lbs. |
| 69. | ---- | | 94. | B. gravity. |
| 70. | ---- | | 95. | ---- |
| 71. | C. | provide a reference to mount accelerometers on. | 96. | C. unbalanced |
| | B. | orthogonal | 97. | ---- |
| | D. | is used to stabilize the stable member. | 98. | D. True |
| | D. | precess about its output axis. | 99. | C. True |
| 72. | ---- | | 100. | B. fall downward about A-A' |

- | | |
|---|-------------------------------|
| 101. ---- | 128. ---- |
| 102. ---- | 129. ---- |
| 103. D. True | 130. ---- |
| 104. C. True | 131. ---- |
| 105. ---- | 132. A. position. |
| 106. D. unbalance | 133. ---- |
| 107. ---- | 134. ---- |
| 108. ---- | 135. ---- |
| 109. B. indicates acceleration. | 136. ---- |
| 110. ---- | 137. ---- |
| 111. A. an angle . | 138. ---- |
| 112. D. all of the above. | 139. ---- |
| 113. A. acceleration | 140. ---- |
| 114. C. 2 | 141. C. shortest |
| 115. ---- | 142. A. True |
| 116. B. C-C' | 143. ---- |
| 117. C. computer | 144. ---- |
| 118. ---- | 145. ---- |
| 119. D. A and B are correct. | 146. C. earth rotation. |
| 120. D. stabilization | 147. ---- |
| 121. ---- | 148. ---- |
| 122. ---- | 149. ---- |
| 123. A. input axis.
C. velocity | 150. ---- |
| 124. B. all of these answers are correct. | 151. ---- |
| 125. ---- | 152. ---- |
| 126. B. True | 153. ---- |
| 127. C. steering signals. | 154. A. north latitude lines. |
| | 155. C. earth's equator. |

156.	B.	longitude.	184.	----
157.	----		185.	A. True
158.	----		186.	----
159.	----		187.	----
160.	----		188.	----
161.	----		189.	----
162.	B.	rhumb	190.	----
163.	D.	great circle	191.	----
164.	----		192.	----
165.	----		193.	----
166.	----		194.	----
167.	----		195.	----
168.	----		196.	C. True
169.	----		197.	B. 15
170.	----		198.	B. True
171.	D.	A and B are correct.	199.	C. a portion of full earth rate.
172.	A.	True	200.	----
173.	C.	known.	201.	----
174.	----		202.	----
175.	----		203.	B. 0 E.R. U.
176.	----		204.	----
177.	----		205.	----
178.	----		206.	----
179.	----		207.	----
180.	----		208.	----
181.	----		209.	----
182.	----		210.	----
183.	D.	senses 1 g.	211.	----

- | | | | | |
|------|------|---|------|---|
| 212. | A. | True | 239. | ---- |
| 213. | ---- | | 240. | ---- |
| 214. | ---- | | 241. | ---- |
| 215. | ---- | | 242. | ---- |
| 216. | ---- | | 243. | ---- |
| 217. | ---- | | 244. | ---- |
| 218. | ---- | | 245. | C. the orbital path of planets. |
| 219. | C. | the up accelerometer will always
be parallel to local gravity. | 246. | B. time, velocity and area. |
| 220. | ---- | | 247. | ---- |
| 221. | ---- | | 248. | B. True |
| 222. | ---- | | 249. | C. time and distance. |
| 223. | ---- | | 250. | D. one half the major axis. |
| 224. | C. | circle. | 251. | ---- |
| 225. | ---- | | 252. | C. the two focii at one point. |
| 226. | D. | ellipse | 253. | ---- |
| 227. | D. | parallel to | 254. | ---- |
| 228. | D. | hyperbola | 255. | ---- |
| 229. | ---- | | 256. | ---- |
| 230. | ---- | | 257. | A. True |
| 231. | A. | major | 258. | C. True |
| 232. | ---- | | 259. | D. it's a standard we picked. |
| 233. | ---- | | 260. | ---- |
| 234. | ---- | | 261. | ---- |
| 235. | ---- | | 262. | ---- |
| 236. | ---- | | 263. | ---- |
| 237. | ---- | | 264. | A. keep track of energy
relationships. |
| 238. | A. | apogee. | 265. | D. dividing the weight of the object
by gravity. |

266. ----
267. ----
268. ----
269. ----
270. ----
271. ----
272. ----
273. ----
274. ----
275. ----
276. ----
277. ----
278. ----
279. A. perigee.
280. D. A and B are correct.
281. D. accelerometers
282. B. accelerometers
283. ----
284. ----
285. ----
286. B. direction of local gravity and
stable member azimuth.
287. C. parallel
288. ----
289. A. establish a horizontal plane.
290. C. VSE case.
291. D. sensor current.
292. A. centered.
293. C. 1 and 2.
294. ----
295. ----
296. ----
297. D. VSE sensors.
298. C. the sensor closest to the bob.
299. ----
300. C. the accelerometers and VSE.
301. A. establish an exact line in that
plane.
302. D. A and C are correct.
303. B. all of these answers are correct.
304. ----
305. C. south.
306. B. True
307. ----
308. ----
309. D. A and B.
310. B. VSE and theodolite
311. C. West
312. A. space.
313. ----
314. ----
315. C. A and D are correct.
316. B. C and D are correct.
317. ----
318. ----
319. A. True

320. D. True
321. D. actual velocity and position to ideal velocity and position.
322. B. missile attitude.
323. D. maybe just before inertially referencing the stable member.
324. ----
325. A. by the computer.
326. ----
327. B. velocity - distance
328. C. a point.
329. B. all of these answers are correct.
330. ----
331. D. zero.
332. ----
333. ----
11. A. time rate of change of velocity.
12. C. a push or pull exerted on a body.
13. B. 4 gm
14. C. 2,940,000 dynes
15. B. the mass of an object times its velocity.
16. C. time rate of change of distance-scalar.
D. time rate of change of distance-vector.
A. time rate of change of velocity.
C. a push or pull exerted on a body.

ANSWERS TO APPENDIX I FRAMES

1. ----
2. A. grams, centimeters and seconds.
3. C. change of position with respect to time.
4. B. 5 cm/sec.
5. B. 12 cm
6. C. time rate of change of velocity.
7. A. 980 cm/sec^2
8. D. 4 ft/sec
9. D. A and B above.
10. B. A and C.