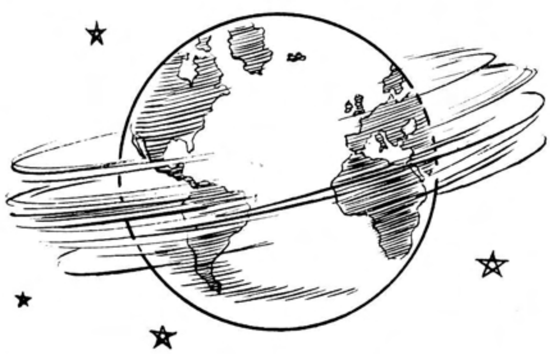
THE GYRO-COMPASS

THE word "gyroscope" is of French origin — a combination of two Greek words, "gyros", meaning turn or revolution, and "skopein", meaning to view, the literal translation of the two words being "to view the revolution" of the earth. The correct pronunciation of the word is with the g soft as in "gentleman". In the first syllable the y is long, as in "sky". Ro is pronounced like the row in rowboat, and scope to rhyme with rope.

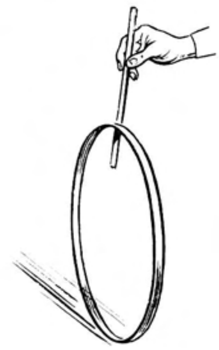
The reason the French have the distinction of originating the name gyroscope is because the great French scientist Leon Foucault was one of the first authorities on the subject of gyroscopic phenomena, having succeeded as early as 1852 in actually producing a gyroscope with which he could observe, with the aid of a microscope, the ceaseless onward movement of the earth's rotation.

If the reader will permit one more slight digression it might be well to remember (before we get down to serious business) that the sphere on which we live is in itself a mammoth gyroscope and that there probably would be no life at all on the earth if it did not revolve like a top, with the direction of its polar axis fairly constant. Otherwise the surface of the earth would be exposed to extremes of heat and cold with such rapidity that living organisms would not be able to survive.



Definition and Principles of the Gyroscope

There is nothing mysterious about the gyroscope. Its actions, though they may appear at first to defy the laws of physics, in reality depend entirely upon Sir Isaac Newton's Laws of Motion.



Many of the toys we used to play with were based on gyroscopic principles. A spinning top is an elementary form of gyroscope, the "diabolo" — once a popular object for pastime — is another; so also is a hoop, for it will exhibit the characteristics of a gyro as long as it has sufficient motion to roll along the ground.

All of the practical applications of the gyroscope are based upon two fundamental characteristics, namely: "Gyroscopic Inertia" and "Precession".

Gyroscopic Inertia, or rigidity in space as it is sometimes known, is the tendency of any rotating body to preserve its plane of rotation. For example, a hoop, when set in motion, will keep on rolling if undisturbed, approximately in a straight line, instead of tipping over as it would if not revolving.

The second characteristic of the gyroscope — Precession — is also exhibited by the rolling hoop. If we wish to change its direction of travel, we do not press against the rim at the front or back, but

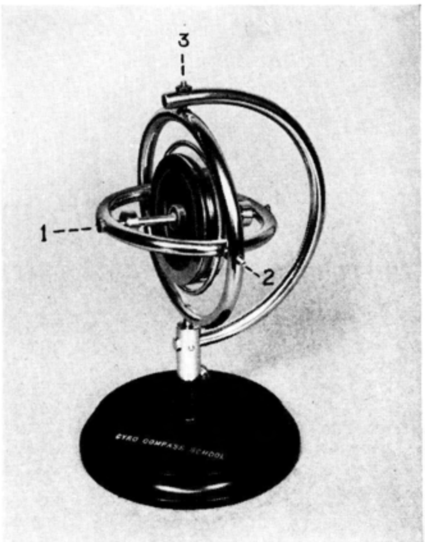


FIGURE 1.
The gyroscope has three axes of angular freedom.

at the *top* — as though we intended to tip it over about an imaginary horizontal axis. The hoop resists this pressure and turns, instead, about a vertical axis which is at right angles to the axis about which the pressure was applied.

If we transform the hoop into a wheel, provide an axle for it, and mount the axle in supporting rings as shown in Figure 1, we can obtain a true gyroscope, which is simply a spinning wheel or mass, universally mounted. Only one point — the geometrical center of its supporting system — is in a fixed position, the wheel being free to turn in any direction around this point. The wheel or rotor is free to revolve in its supporting ring about axis 1. The supporting ring is free to revolve in an outer ring about axis 2 which is always at right angles to the axis of rotation of the wheel. The outer ring, likewise is free to revolve in pivot bearings in a supporting frame about axis 3 which is always at right angles to the axis of rotation of the inner ring.

With this arrangement, the axle can be pointed in any direction without altering the geometrical center of the assembly. When such a wheel is spinning, it exhibits exactly the same characteristics as the hoop, but does so without having to be rolled along the ground. "Gyroscopic inertia" may be illustrated by spinning the rotor and placing it in the position shown in Figure 2. If the base of the gyroscope is tilted, as shown in Figure 3, the rotor, instead of tipping over, as it would if not revolving, maintains its original plane of rotation. It will continue to do so, no matter how much the base of the gyro is moved about, as long as it continues to spin with sufficient velocity to

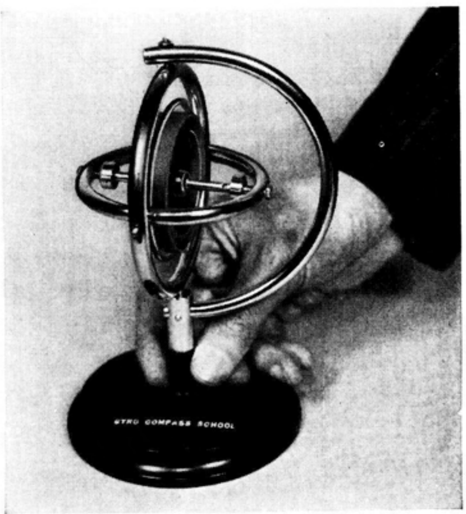


FIGURE 2.
When spinning, the gyro exhibits "gyroscopic inertia".

FIGURE 3.
The original plane of rotation is maintained no matter how the base is moved about.

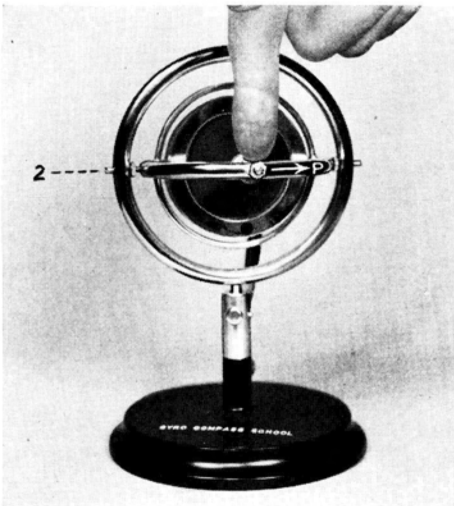


FIGURE 4.
Precession about the vertical axis.

overcome the friction between itself and its supporting bearings.

This characteristic is the result of the action of forces affecting the state of rest and motion of a gyroscope in the manner expressed by Newton's First Law of Motion, which states that *every body continues in its state of rest or of uniform motion in a straight line, unless it is compelled by forces to change that state.* This law as applied to a rotating wheel may be expressed by stating that a rotating wheel tends to maintain the direction of its plane of rotation in space and the direction of its axis in space.

"Precession" may be illustrated by applying a force or pressure to the gyro about the horizontal axis as shown in Figure 4. It will be found that the applied pressure meets with resistance and that the gyro, instead of turning about its horizontal axis, turns or "precesses" about its vertical axis in the direction indicated by the arrow P. Similarly, if we apply a pressure about the vertical axis, the gyro will precess about its horizontal axis as shown at P in Figure 5. If there were a complete absence of inertia and friction about the precessional axis, the rate of precession would be such that the resistance of the gyro would be exactly equal to the applied pressure at any instant, and no movement from this pressure could ensue until the gyro had precessed so that its plane of rotation coincided with the plane of the applied pressure. Then the precession would cease and, with it, all resistance to the applied pressure.

A convenient way to remember the direction in which precession takes place is to regard the pressure as though it acted at a single point on the rim of the wheel, as indicated by the black dot in Figure 4. This point will not move, in response to the pressure, but a point 90 degrees beyond, in the direction of the wheel's rotation, will move away instead.

There you have the gyroscope in a nutshell, but inasmuch as the next step will be an explanation of the reason for precession, you may wish to ask a question or two at this point. You might like to ask, for instance, why it is that of the many rotating objects with which you are familiar, some display gyroscopic phenomena and others do not. Why does a *top* exhibit gyroscopic characteristics while an engine flywheel, which also spins with high angular velocity, does not? Why does a *rifle bullet* behave like a gyroscope while a *windmill* merely behaves like a windmill?

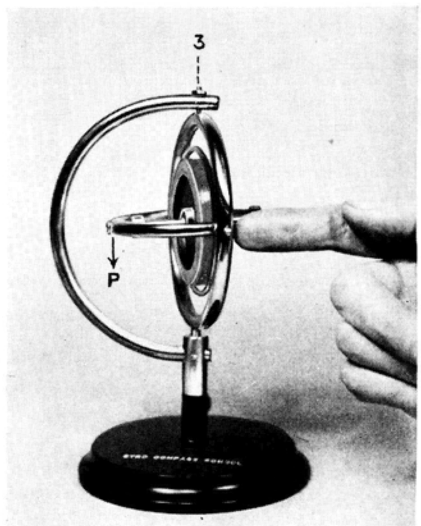


FIGURE 5.
Precession about the horizontal axis.

Gyroscopic properties are inherent in all rotating masses, but can best be observed in those which have the greatest amount of freedom about two axes in addition to the spinning axis. The top comes under the latter category. The engine flyweel, on the other hand, is limited to one angular axis of freedom — its spinning axis. A rifle bullet may be likened to a gyroscope because it is free to revolve about two other axes, in addition to its spinning axis; therefore it exhibits gyroscopic inertia, tending to maintain a straighter line of flight than it would if not rotating. A *windmill* has freedom about its spinning axis and also about a vertical axis (as it must be able to turn in any direction under the control of its rudder). It has no freedom about a horizontal axis other than its spinning axis, however, and therefore, although precessional forces are impressed upon the apparatus by shifts of wind, there are no visible effects. The precessional forces result in a torque which is absorbed in the bearings. In a windmill these forces are small, however, owing to the light construction of the fan. In order to obtain maximum gyroscopic effects a rotor should be comparatively heavy, with as much of its weight concentrated at the rim as practicable, and it should spin with considerable velocity. Gyroscopic inertia depends upon angular velocity, weight and radius at which the weight is concentrated. Maximum effect is obtained therefore from a mass, with its principal weight concentrated near the rim, rotating at high speed.

Reason for Precession

The reason for precession may be explained quite simply if we consider the mass of the rotor to be concentrated in separate particles such as A, B, C, and D in Figure 6. Figure 6 is a section through the center of the rotor, just as though you sliced it in half with a knife, threw the upper half away and lay the bottom half on the paper. We will assume that the wheel is spinning with considerable velocity in the direction of the arrow R at the top, and we will select that instant in the cycle when the particles are in the positions shown in Figure 6. If we can show what will happen to four particles equally spaced as are A, B, C, and D, we can show what happens to the entire rotor, since all other particles within it act in the same manner.

In order to make the explanation clearer we will simulate the movements of the rotor by corresponding motions of the booklet itself, and as a first step in this direction we will lay the booklet flat upon the table.

Now let us assume that a force F is applied against the rotor just as though we pressed down against the paper with a pencil at this point — as though we tipped the top of the booklet *down,*

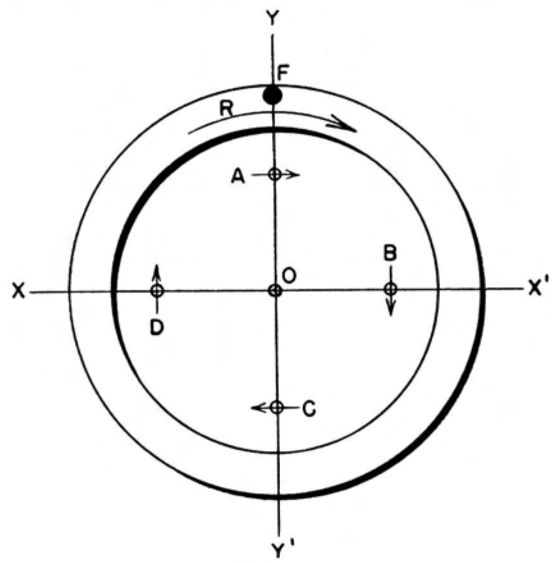


FIGURE 6.

Gyro rotor shown in section. For the sake of clarity its mass is considered to be concentrated in the four separate particles, A, B, C, and D.

the bottom *up.* This would tend to rotate the wheel about the axis X-X′. Sir Isaac Newton said, in effect, that all matter is pigheaded or stubborn — that it will continue to move in a straight line unless disturbed, and if disturbed, it will offer resistance to the disturbing force. Let us see what happens to particle A. This particle was moving to the right before we started pushing down at F. Now, however, it tends to move to the right and *down* into the paper — a combination of the motion due to the wheel's rotation and the motion due to our applied force F. Likewise particle C, which was moving to the left, now tends to move to the left and *up* out of the paper.

As a result of these motions the wheel actually turns about the axis YY′ which is at right angles to the axis about which the force F was applied. Its motion is the same as though we tipped the right hand side of the booklet *down,* the left *up.* This is precession.

The reader will probably ask: "What happens to B and D?" Since B and D lie in the axis about which the force F is applied, they are unaffected by that force. Like A and C, however, they are pigheaded and want to have their own way.

Because of the wheel's rotation, B moves toward the bottom of the page, D toward the top. But the wheel is now turning about axis YY′ because of its precession. Therefore B tends to move toward the bottom of the page and *down* into the paper, D tends to move toward the top of the page and *up* out of the paper. In a perfectly balanced gyro operating without friction, the sum of these motions would exactly offset the force F, so that no motion could take place about axis XX′. Thus the only motion which could result from the application of a force as at F would be precessional rotation about an axis at right angles to the axis about which the force is applied. In other words, the wheel moves in the direction of the least resistance to any force which tends to disturb its plane of rotation — and the point of least resistance is always 90 degrees away in the direction of the wheel's rotation.

OPERATING PRINCIPLES OF THE GYRO-COMPASS

In the Gyro-Compass the characteristics of the gyroscope, "inertia" and "precession", which we have just explained, are combined with two constant, natural phenomena — the earth's rotation and the force of gravity, with the result that the instrument aligns itself with the *geographic* meridian and provides a constant true north indication regardless of the rolling, pitching, and yawing of the vessel.

Apparent Rotation

Let us consider the gyro to be mounted at the equator with its axle east and west. We will observe its behavior from a point in space beyond the South pole as shown in Figure 7. To avoid confusion we will dispense with the supporting rings in this and subsequent illustrations, and show only the wheel and axle of the gyro, as these are the parts with which we are concerned chiefly.

The earth turns in the direction of the arrow, or clockwise, with an angular velocity of one revolution every 24 hours, carrying the gyro around with it; but the gyro, because of its inertia, maintains its original plane of rotation in regard to *space* just as it did when its base was tilted as shown in Figure 3. With respect to the *earth,* however, the gyro rotates about its horizontal axis with an equal velocity (one revolution in 24 hours) but in the opposite direction to the rotation of the earth. After three hours the end of the axle which was pointing east apparently is elevated at an agle of 45 degrees; after six hours, 90 degrees; after twelve hours, 180 degrees; and so on, until, at the end of 24 hours, it is back where it started.

Similarly, if we consider the gyro to be placed either at the North or the South pole at the theo-

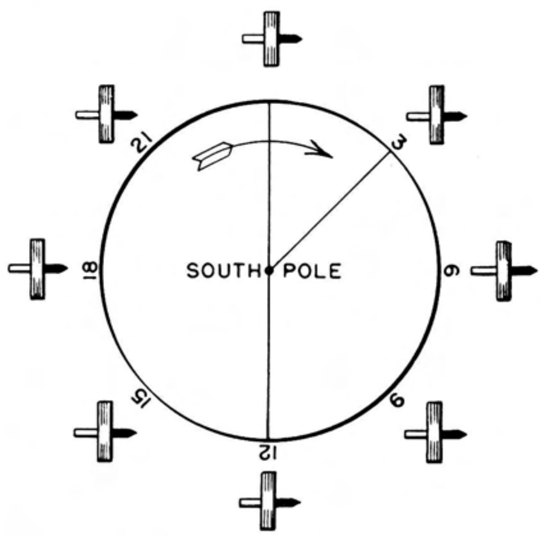


FIGURE 7.

A gyro with its spinning axis set in the East-West position at the equator appears to turn about its horizontal axis once each twenty-four hours.

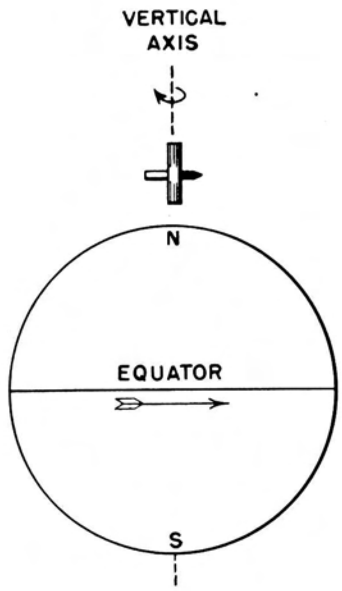


FIGURE 8.

A gyro with its spinning axis set horizontal at the Pole appears to turn about its vertical axis once each twenty-four hours.

retical axis of rotation of the earth, with the axis of the gyro horizontal, as shown in Figure 8, the gyro will appear to rotate, but this time about its vertical rather than its horizontal axis.

At points between the poles and the equator the gyro appears to turn partly about the horizontal axis and partly about the vertical, because it is affected by both the horizontal component and the vertical component of the earth's rotation. See Figure 9. The horizontal component of the earth's rotation causes the north end of the axle to rise. The vertical component causes it to turn to the east.

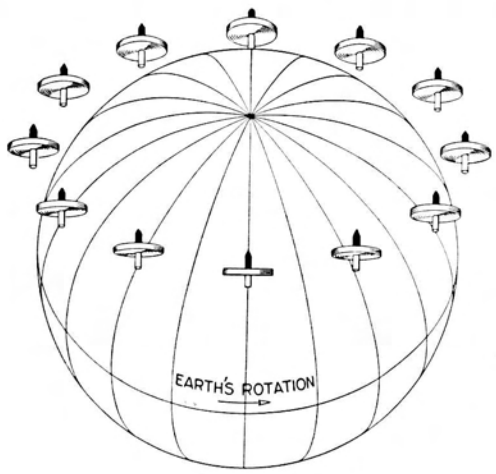


FIGURE 9.

A gyro with its spinning axle set horizontal at any point away from the equator maintains its plane of rotation in space and apparently moves about both its horizontal and vertical axis.

The reader will perceive that the difference between gyroscopic inertia and apparent rotation is simply one of *point of view*. As far as *space* is concerned the gyro remains fixed. In comparison with the earth, however, the gyro actually rotates as described above. It is this rotation which makes it possible to apply the force of gravity so as to convert the gyroscope into a North seeking gyro-compass.

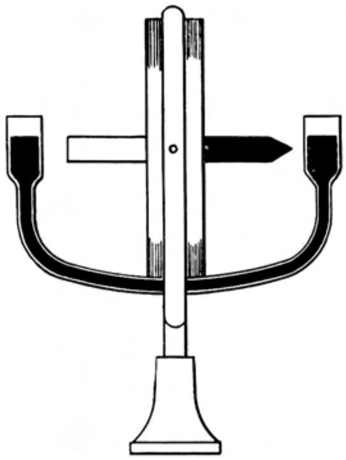


FIGURE 10.

To make the gyro *seek* the North a mercury tube is added, its effect being applied about the horizontal axis.

The first step in this direction is to cause the gyro to precess toward the meridian. Figure 10 shows diagrammatically a gyro to which has been added a pair of containers with interconnecting tube; the assembly is partially filled with mercury and is attached to the gyro frame in such a way that it will tilt with the gyro when the gyro tilts or rotates about its horizontal axis. With the gyro at the equator and horizontal as shown at A in Figure 11 the mercury is distributed equally in the tube and its weight exerts an equal downward pressure on each end of the axle. Therefore, in

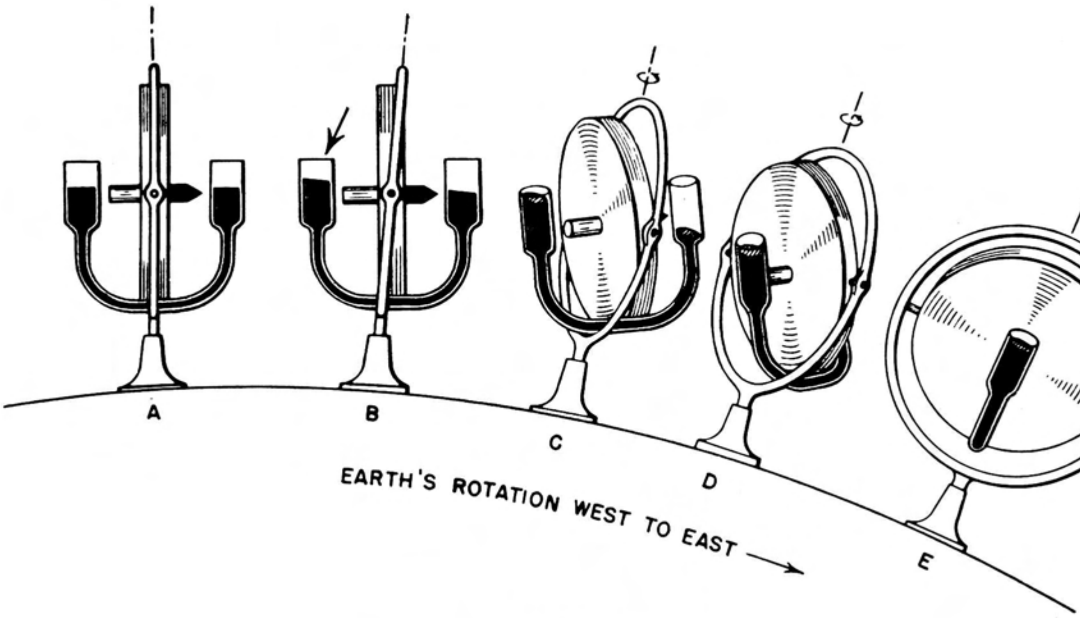


FIGURE 11.
Effect of the mercury ballistic when applied about the horizontal axis.

this position, the mercury has no effect upon the gyro. As the end of the axle which is pointing east (the right-hand end) slowly rises, some of the mercury, under the influence of gravity, is transferred to the lower end of the axle, as shown by the arrow at the left in B of Figure 11. In this position a force is being exerted about the horizontal axis; the effect of the mercury being the same as though we were to push down on the west end (the left-hand end) of the gyro axle. The result is that the gyro precesses about the *vertical* axis as shown by the small arrows at the top in C and D, the axle turning slowly counter-clockwise. As the end of the gyro which at first was pointing east (which we shall now refer to as the north end) precesses toward the meridian, it continues to rise, under the influence of the earth's rotation. After the gyro axle has precessed so that it is parallel to the meridian, the excess mercury at the south end causes its precession to continue, and the end of the gyro axle which was at first pointing west (which we shall now refer to as the south end) is carried to the east of the meridian. This south end now commences to rise and the mercury starts flowing back to the North end, precession being gradually diminished until the axle is again horizontal and the mercury evenly distributed. At this point precession of the north end toward the West ceases. The south end continues to rise, however, because it is still east of the meridian, and at length the mercury in the north side of the tube overbalances that in the south side. Precession, therefore, is reversed, and the north end returns toward the meridian, declining more and more as the south end continues to rise. This oscillation of the gyro about the meridian may be clearly understood by referring to Figure 12 which shows the movements of the gyro axle projected onto a vertical plane. The ellipse in Figure 12 is the result of a displacement of the gyro axle of only a few degrees from the meridian. If the gyro axle were pointing east and west at the beginning of the cycle, as shown in Figure 11, precession would take place through 180 degrees in each direction, and at one extreme the north end of the gyro axle would point East, at the other, West. In any case the gyro never comes to rest, as there is no force tending to restore its axle to a horizontal position until after it has passed the meridian.

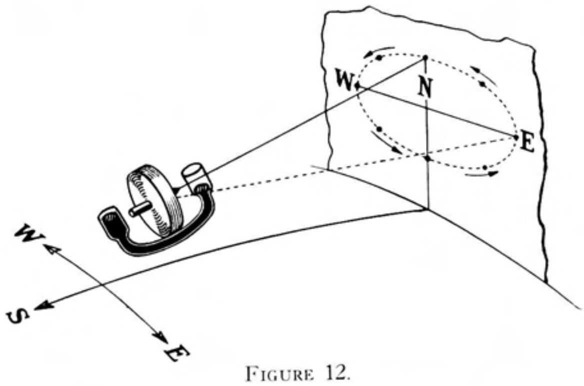


FIGURE 12.

Diagram showing the movement of a mercury-controlled gyro wheel when set with its axle pointing east of north.

The ratio of the movement about the horizontal axis (caused by "apparent rotation") to the precessional movement about the vertical axis (caused by the flow of mercury) determines the shape of the ellipse. If the free surface of the mercury in the containers is increased so that more mercury can be transferred, the rate of precession will increase and therefore the ellipse will be flatter. If the mercury effect is decreased, the rate of precession will diminish to a point where the ellipse would, theoretically, be almost circular.

In the preceding paragraphs we have explained the behavior of a gyro under the simplest form of mercury control, the mercury being attached directly to the ring, frame or casing which supports the gyro. With such an arrangement the mercury can act only about the horizontal axis, and the gyro, therefore, will precess only about the vertical axis. An additional pressure is required about the vertical axis in order to generate precession about the horizontal axis which will counteract the natural tendency of the gyro axle to tilt. The manner in which this is accomplished will be shown in the following paragraphs.

It will be necessary first, however, to explain the basic elements of an actual gyro-compass. As shown in Figure 13 the rotor is contained in a case (1) and the case is supported on horizontal bearings in a vertical ring (2). The rotor-case and the vertical ring are free to turn about the vertical suspension axis (3). Although the gyro-compass, as shown in Figure 13, necessarily differs in its details of construction from the model gyros shown in some of the previous illustrations, it has the same angular freedom about its spinning, horizontal, and vertical axes, and exhibits exactly the same characteristics.

Figure 13 shows the addition of an outer frame (4) called the phantom, which is driven by an electrical follow-up system so that it follows every movement of the gyro about the vertical axis. By supporting the mercury tube or ballistic (5) in bearings in the phantom ring we can obtain a controlling action about the vertical axis of the gyro so as to arrest its oscillations and cause it to align itself with the meridian.

This is accomplished by connecting the mercury ballistic to the gyro case at a point (6) *slightly to the east of the vertical centerline.* With this arrangement the major effect of the mercury still acts about the horizontal axis and causes the gyro to precess toward the meridian as before; but there is now an additional effect about the vertical axis which causes the gyro to

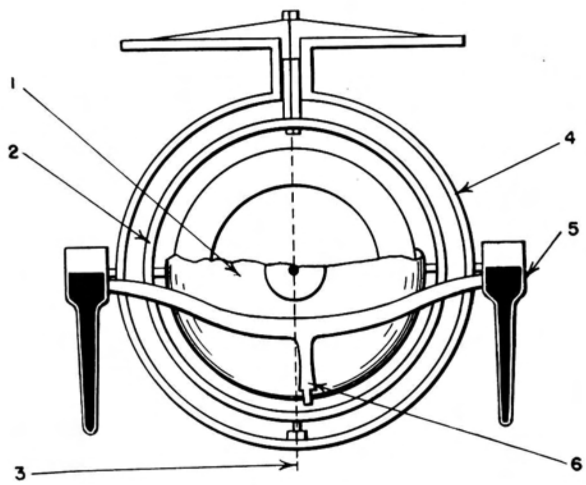


FIGURE 13.

Elements of the Gyro-Compass.

In order to obtain a more symmetrical construction, the mercury ballistic consists of two sets of containers and tubes, instead of the single pair of containers shown in preceding illustrations.

precess about the horizontal axis, introducing a tilt of the gyro counter to the natural tilt resulting from "apparent rotation". The end of the axle will therefore follow a spiral path as shown in the polar diagram, Figure 14. The reduction of the oscillation which is produced by the action of the mercury ballistic about the vertical axis is called "Damping". A careful consideration of the action of the mercury ballistic will make it apparent that the only position of rest which the gryo can find *at the equator* will be with its axle horizontal and in the meridian. In other words, we have obtained a true, meridian-seeking Gyro-Compass.

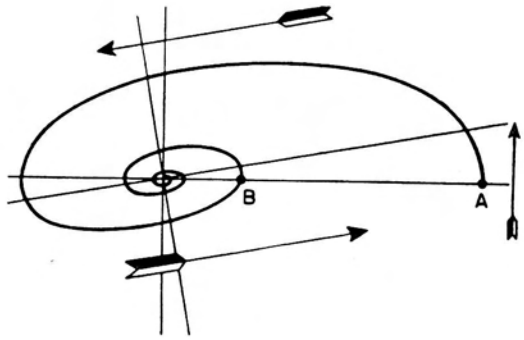


FIGURE 14.
Action of the gyro axis when the mercury ballistic is connected to its casing through an eccentric pivot.

A number of other factors must be considered, however, before we can obtain a gyro-compass which will function accurately and reliably, at various latitudes, on a rolling, pitching vessel moving over the earth's surface at considerable speed.

We have seen that the action of the mercury ballistic about both the horizontal and vertical axes is made possible by the use of the phantom element. This element serves another important purpose: it provides a means of suspending the gyro so that it is practically free from friction about its vertical axis. The gyro is supported from the top of the phantom by steel wires and the phantom is kept in exact alignment with the gyro by means of an electrical follow-up system. The compass card is a part of the phantom element, the whole of which is supported on ball bearings from the main supporting frame or "spider". Thus, with the exception of the eccentric connection between the mercury ballistic and the gyro case and the upper and lower guide bearings, which are practically frictionless, there is no physical contact which can result in any friction between the sensitive gyro element and the compass card or other external parts.

If the compass were to be used on shore, it would be feasible to control the gyro simply by suspending a weight from the phantom, like a pendulum, and connecting the weight to the eccentric pivot on the bottom of the rotor case. This would be impractical on board ship, however, where a compass is subjected to rolling movements in an inter-cardinal plane (northeast to southwest, or northwest to southeast). Inter-cardinal rolling causes a compass to swing in its gimbals, with the result that the pendulum would be subjected to acceleration forces which would cause a continuous torque about the vertical axis of the compass.

One way of avoiding this effect would be to stabilize the compass gyroscopically and so prevent it from swinging. In the Sperry compass, however, the complication of stabilizing gyros is avoided by the use of the mercury ballistic, which controls the gyro as we have already explained. The mercury ballistic is non-pendulous: its weight is distributed equally above and below the gyro axle so that it is neither top-heavy nor bottom-heavy. Therefore, no acceleration forces are generated and no torque about the vertical axis of the compass is introduced by the swinging of the compass in its gimbals.

Under slow rates of inclination such as those produced by the earth's rotation, the action of the mercury ballistic is equivalent to that of an ordinary pendulum, but opposite in direction. Under rapid rates of movement, however, the small bore of the mercury tubes prevents the mercury from surging back and forth and introducing errors in the compass.

Damping Factor

The extent of the damping action is governed by the displacement of the mercury ballistic connecting link from the centerline. Commercial compasses are given a damping factor of 66%, i. e., the eccentricity of the connecting link is such that each swing of the gyro axle from the meridian is one-third of the preceding swing, the amplitude being reduced by 66% at each oscillation. If the compass is started 30 degrees east of the meridian, the first swing will carry the compass to 10 degrees west, the return swing to 3-1/3 degrees east, then 1-1/9 degrees west, and so on, until it comes to rest. Figure 15 shows graphically the damping characteristics of the gyro-compass.

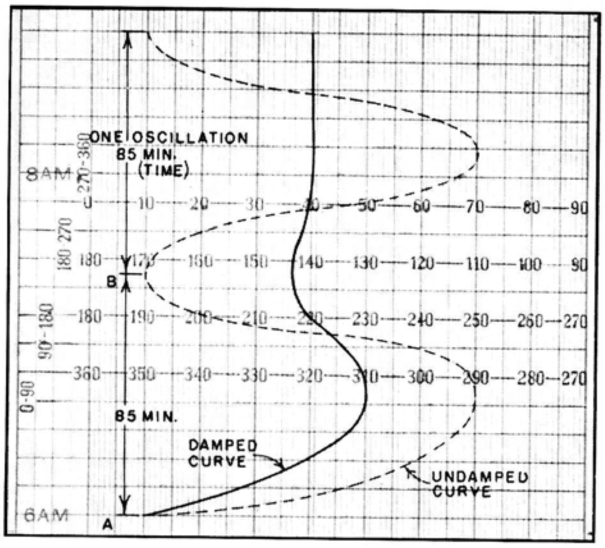


FIGURE 15.

Gyro-Compass damping curve as charted by a course recorder operated from the master compass. A shows settling characteristics when compass is set 30° away from the meridian. B shows undamped oscillations. Chart is read from bottom up.

Period of Oscillation

The natural period of the compass, i. e.: the time it takes to perform a complete oscillation (from A to B in Figure 14) is 85 minutes. The period of oscillation is governed by two factors:

1. The angular momentum of the gyro (the product of weight, speed and square of radius of gyration) and
2. The torque about the horizontal axis supplied by the action of the mercury ballistic. (This, in turn, is governed by the free surface of the mercury in the containers and the distance of the containers from the horizontal axis.)

If the weight or the speed of the gyro is increased, the period of oscillation will be longer. If the free surface of the mercury is increased, the period of oscillation will be shorter.

The compass is designed with this long period so as to function satisfactorily on a moving ship at sea. A compass with a much longer or much shorter period would have an incorrect ballistic deflection and would show some deviation when turning.

Compensating Weights

Unsymmetrical distribution of weight is another potential source of disturbance, when the compass is swinging, which must be neutralized. When the unsymmetrical weight shown in Figure 16 is swung in the plane A-B, centrifugal stresses act upon it in such a way as to cause all of its particles to place themselves as far as possible from the axis of swing. This causes a tendency to turn, as indicated by the arrows. The same effect may be observed when a watch is swung back and forth on its chain through a small arc. In the gyro-compass this effect is avoided by the use of compensating weights which permit of a symmetrical distribution of weight about the vertical axis.

The foregoing explanation applies particularly to a compass at the equator and in a vessel which is not under way. At points other than the equator and on board ships which are moving over the surface of the earth, certain factors are introduced which would result in errors if they were not compensated or corrected in the design of the compass.

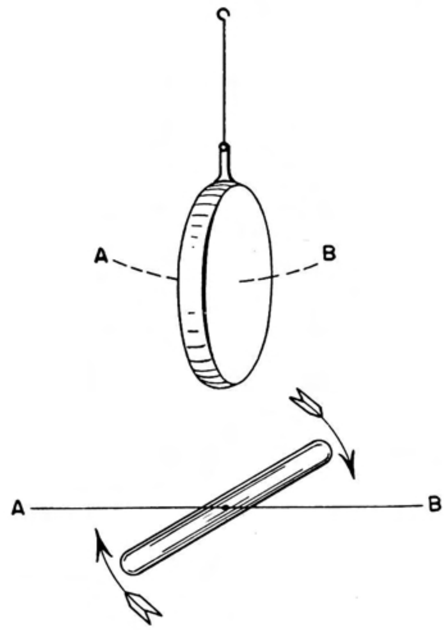


FIGURE 16.
Effect of unsymmetrical distribution of weight.

Latitude Correction

The latitude correction is necessary because of the eccentric connection employed to damp the oscillations of the compass. The correction is made by means of a latitude adjustment scale, no special knowledge of the problem being required in order to make the correction. A complete explanation of the reasons for the latitude error, however, will be welcomed by the student because it involves a general discussion of compass behavior and will give the student an opportunity to find out some of the whys and wherefores that might otherwise escape attention.

At the equator, where only the horizontal component of the earth's rotation affects the gyro, the axle of the compass is horizontal and parallel to the earth's axis. At the equator, therefore, as soon as the compass has settled on the meridian, the ballistic will be at rest and the compass may be considered as a true gyroscope.

If we move the compass to a point to the north or south of the equator, however, it will be affected by the vertical as well as the horizontal component of the earth's rotation. At a point north of the equator, for instance, the north end of the gyro axle tends to turn toward the east and rise, as the earth rotates out from beneath it. This was illustrated in Figure 9. It is apparent that the north end of the gyro axle must be precessed continuously in a westerly direction toward the meridian as fast as it is being displaced by the vertical component of the earth's rotation. The force necessary to do this is obtained automatically by the simultaneous tilt of the mercury ballistic which permits an accumulation of mercury in the lower or south containers so as to precess the axle continuously toward the meridian.

If it were not for the offset connection of the mercury ballistic, the gyro axle would eventually settle, theoretically, exactly on the meridian, with the end away from the equator tilted up just enough so that there would be sufficient excess mercury in the containers toward the equator to precess the gyro toward the meridian at the same rate as it is being carried away by the vertical component of the earth's rotation.

In order to damp the oscillation, however, the mercury ballistic connection is offset to the east of the centerline of the compass. This produces a counter-clockwise torque about the vertical axis, causing the north end of the axle to precess continuously *down.* The axle, therefore, settles to the east of the meridian (in north latitudes) at a point where the downward precession of the axle due to torque about the vertical axis is exactly balanced by the horizontal component of the earth's rotation tending to tilt the north end up.

As we move the compass further north, the north end of the gyro axle turns to the east faster and rises faster, and for this reason the compass must be precessed faster toward the meridian. The downward pressure on the south end of the axle is correspondingly greater, the torque about the vertical axis is greater, the north end precesses down faster, and the gyro consequently settles further to the east.

South of the equator the effect of the earth's rotation on the gyro is just the opposite: here the *south* end of the axle tends to rise and turn to the east; the excess mercury is in the north containers, precessing the *north* end to the east toward the meridian. Torque about the vertical axis is reversed, so that the south end is being precessed down at the same rate as the horizontal component of the earth's rotation is tilting it up. Therefore the north end of the axle lies slightly to the *west* of the meridian.

The small angle at which the gyro axle settles from the meridian varies with the latitude, and for this reason a correction must be introduced which will compensate for this natural error at any latitude where the compass may be expected to be used.

From zero at the equator, this error increases to 2.9 degrees at 60 degrees north or south latitude; it is easterly in north latitudes and westerly in south latitudes.

No attempt is made in the gyro-compass to compel the axle to seek a resting place at variance with its natural settling position. Instead, a latitude adjustment is provided which moves the lubber ring the necessary amount to cause the compass indication to be true. Since the transmitter is mounted on the lubber ring a correctional movement applied to the lubber ring also transmits the corrected reading to the repeater compasses, course recorder and gyro-pilot for automatic steering. This is the "Latitude Correction", and is made independently of the speed and course correction, described below.

Ship's Speed and Course

It has been shown that the relatively slow angular movement of the earth's rotation (only one revolution in 24 hours) provides the motive force for the north-seeking precessional movement of the compass. When a vessel is traveling over the earth's surface, however, and therefore about the earth's center, the vessel's movement is compounded with that of the earth. If the direction of travel is east or west, the vessel's motion only adds to or subtracts from the earth's motion, and the effect on the indication of the compass is negligible.

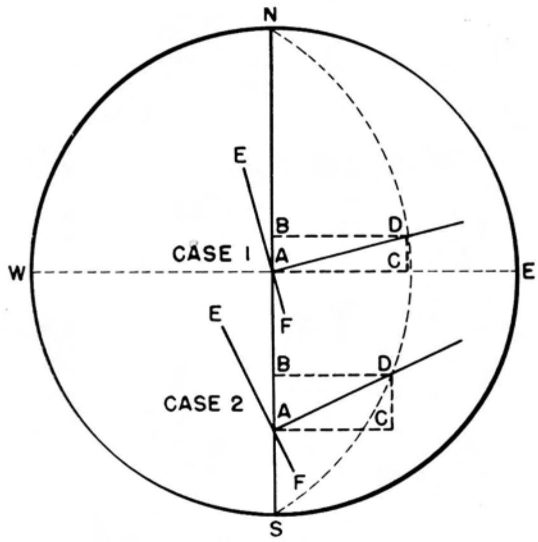


FIGURE 17.

Diagram illustrating the effect of ship's speed and latitude on the gyro-compass.

When the vessel is traveling north or south, however, the effect is a maximum because the ship's speed produces a resultant which is not parallel to the plane of the earth's rotation. The effect on compass indication is proportional to the ship's speed and course and is explained as follows:

In Figure 17 (Case 1) the line AB represents the movement of a vessel steaming due north for a given period of time. Line AC represents the movement of the earth in the same period of time. The actual path taken by the vessel relative to the earth's rotation is AD. AC is the normal plane of rotation. AD is the actual plane of rotation due to combined movement of earth and ship. As far as the gyro-compass is concerned, therefore, a new meridian EF is produced which is at right angles to the line AD. At higher latitudes the movement of the earth is relatively smaller, the new, apparent meridian is displaced farther from the actual meridian, and a larger correction is required. Thus the amount of the correction is dependent upon the latitude of the ship. (Case 2 of Figure 17.)

The displacement of the gyro axle is to the west for northerly courses and to the east for southerly courses, and the angular difference between the actual meridian and this new apparent meridian depends upon:

1. The ship's speed
2. The ship's course, as it is only the northerly or southerly components of the course which are to be taken into account, and—
3. The latitude, as the higher the latitude the smaller the earth's surface speed and therefore the greater the effect of the ship's speed.

The compass is provided with a corrector mechanism which automatically applies the correction due to course and speed at any given latitude by moving the lubber line the required amount to compensate for this error. The compass indicates the ship's true heading on all courses, and no corrections have to be applied by reference to tables.

DESCRIPTION OF THE GYRO-COMPASS

Rotor and Case

Our description logically starts with the rotor, which may be considered as the heart of the entire compass system. The rotor and the case within which it spins are shown in Figure 18. It will be observed that the internal rim of the wheel carries the rotor bars and laminations of an induction motor and that the stator winding of this motor is carried on the inside of the gyro casing. Application of alternating current to the stator winding produces a rotating magnetic field which carries the gyro wheel around with it at a speed of 6,000 revolutions per minute. The gyro axle, shown in the illustration, revolves in ball bearings carried in bearing housings in the ends of the rotor-case. A spirit level, carried on the south side of the rotor-case and parallel to the rotor axle, shows whether the axle is horizontal. It is used when starting the compass and setting it on the meridian.

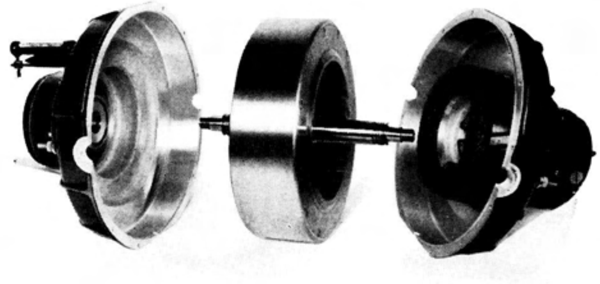


FIGURE 18.
Rotor and case.

Vertical Ring

The rotor-case is supported in horizontal bearings in a vertical ring, as shown in Figure 19. Attached to the vertical ring and projecting out beyond each end of the gyro axle are brackets which support the compensating weights. The purpose of these weights, as shown in Figure 16, is to effect a symmetrical distribution of weight about the vertical axis of the compass. At the top of the vertical ring, in the center, is the steel wire suspension by which the weight of the entire sensitive element is supported within the outer or phantom ring. The wires of the suspension are secured in a stud at the top of the vertical ring

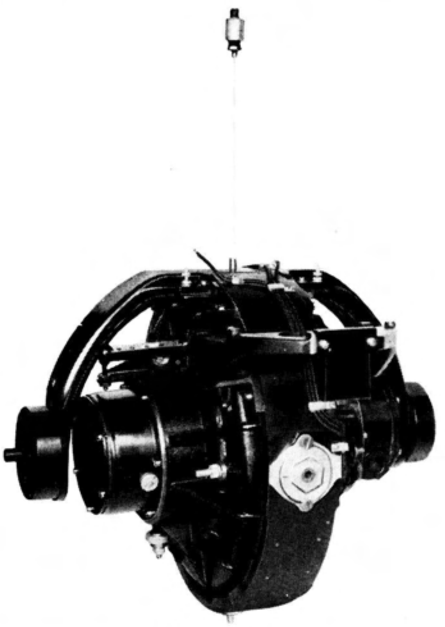


FIGURE 19.
The rotor-case is supported on horizontal bearings in the vertical ring.

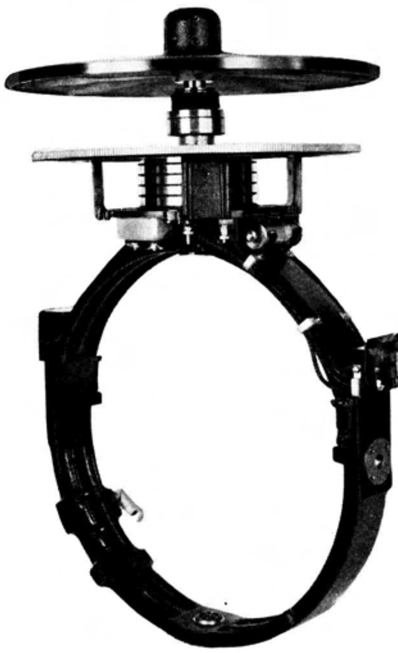


FIGURE 20.
The phantom element.

which forms the inner race of a ball bearing in the phantom ring. This bearing serves as a guide for the movement of the sensitive element about its vertical axis. There is a similar stud at the bottom of the vertical ring. A bracket attached to the "east" side of the vertical ring above the horizontal axis carries the armature of the follow-up system. This armature operates in conjunction with a pick-up transformer on the phantom ring, initiating a signal current which is amplified to control an azimuth motor in such a way that it causes the phantom ring to follow every movement of the sensitive element about the vertical axis.

Phantom Element

Although the directive force of the commercial gyro-compass is 150 times as great as that of a magnetic compass, it would not be sufficient to operate repeater compasses and other accessory equipment if some method were not available to prevent friction from disturbing the sensitive gyroscopic element as the vessel turns around it. The power-driven phantom element accomplishes this purpose. The suspension wires of the vertical ring are passed through the hollow stem at the top of the phantom ring, which is supported from the hub of the compass frame or spider on a ball thrust bearing so that it can rotate freely about the vertical axis. The phantom element is shown in Figure 20.

An azimuth motor causes the phantom ring to follow every movement of the vertical ring so that no twist is developed in the wire suspension, and the "O" and "180" degree marks of the compass card, which is attached to the top of the phantom element, are kept in exact alignment with the north-south axis of the gyro. This system of support provides a practically frictionless mounting of the sensitive element.

Mercury Ballistic

The mercury ballistic is shown in Figure 21. It is supported from the phantom element on horizontal bearings and is connected to the rotor-case by means of an arm attached to the ballistic and a bearing secured to the bottom of the rotor-case. The ballistic connection bearing is offset to the east of the vertical axis of the compass in order to obtain the necessary controlling action about the vertical axis, as explained in the preceding chapter. There are two pairs of mercury reservoirs, one pair on the west and one pair on the east side of the ballistic. The reservoirs of each pair are connected by means of a tube of small diameter, through which the mercury can flow freely in the north-south plane of the compass between the reservoirs on each side. The weights mounted on the studs on the reservoir covers are balance weights; their purpose is to

FIGURE 21.
The mercury ballistic.

make the mercury ballistic non-pendulous about the horizontal axis.

Spider Element

The compass frame or spider element, shown in Figure 22, supports the phantom element on a thrust bearing so that the phantom element can rotate freely about the vertical axis of the compass. The trunnions of the spider element are supported in athwartship bearings in the gimbal ring. The brushes near the center of the spider engage the slip rings on the phantom stem to carry current to the rotor-case for driving the gyro and to the signal transformer for energizing the follow-up system. The spider has a concentric outer ring called the lubber ring, engraved with a lubber line, in relation to which the compass card is read.

Speed Corrector

The speed corrector (Figure 23), the function of which was explained fully on page 16, is mounted on the spider frame. The corrector is fitted with an arm carrying a roller which operates in a "course cosine" cam groove in the under side of the azimuth gear. An adjusting knob on the top of the corrector causes a latitude scale to move over a plate engraved with speed curves. The knob is adjusted until a point is reached where the latitude as marked on the scale intersects the curve corresponding to the ship's speed. Thereafter, corrections for all courses are introduced automatically in accordance with the cosine of the heading by means of the cosine cam and the mechanical linkage in the corrector. The eccentricity of the cosine cam is such that the movement of the lubber ring is zero for easterly or westerly courses (where no correction is required) and a maximum for northerly or southerly courses (where maximum correction is required). The mechanical linkage is so arranged that no correction is introduced unless a definite latitude is set to a definite speed. As the adjusting knob is turned to move the latitude scale from the top of the plate down across the speed curves, however, the linkage begins to take effect and the lubber ring is displaced, provided that the vessel is on other than an easterly or westerly heading. For example, suppose the ship is heading east and turns to north. If the scale were set to zero, no correction would be introduced, even though the effect of the cam would be a maximum, be-

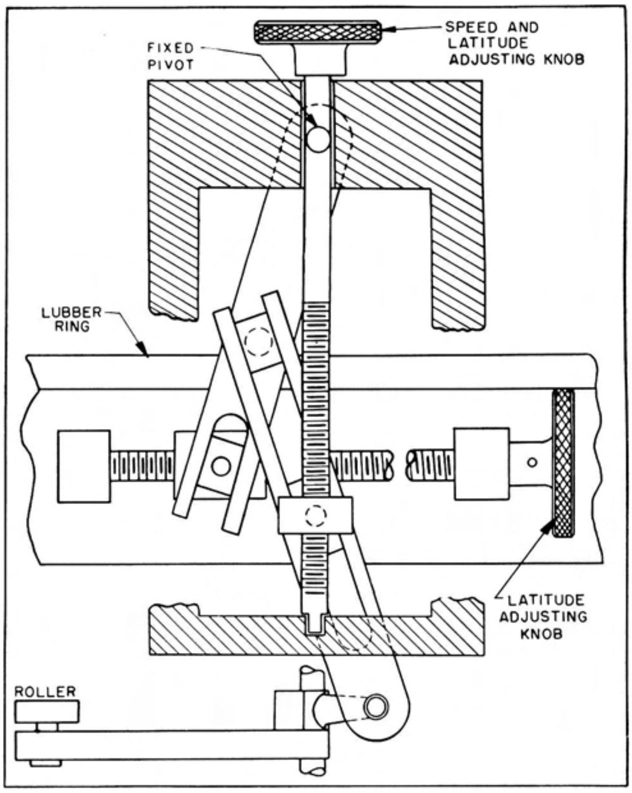


FIGURE 23.
Speed and latitude corrector mechanism.

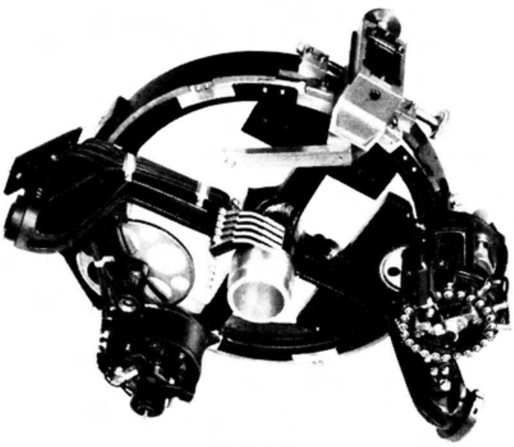


FIGURE 22.
The spider element.

cause the position of the mechanical linkage would nullify its action. If the scale were set to maximum speed and latitude, however, a maximum movement of the lubber ring would be obtained, because then the linkage would be set to the position of its most effective leverage. Any intermediate setting produces proportionate correction.

Latitude Corrector

A latitude corrector, fitted with adjusting knob and scale, is mounted on the lubber ring. By means of this corrector the lubber ring may be shifted one way or the other a few degrees to correct for the natural latitude error described on page 15. The latitude corrector, which functions independently of the speed corrector, introduces the required latitude correction irrespective of the ship's speed or course.

The speed corrector and the latitude corrector are used as follows: When the ship is at sea, true indications for any heading at any latitude are obtained by setting the speed and latitude correctors to correspond to the ship's speed and latitude. When the ship is at the dock or at anchor, true indications for all headings and at all latitudes are obtained by setting the latitude corrector to correspond to the latitude. The scope of the correctors is from zero to 70 degrees latitude and for speeds up to 30 knots. Correct compass indications can thus be obtained over all of the navigable waters of the globe at all of the speeds normally associated with merchant vessels.

Transmitter

The transmitter, for electrically transmitting the indications of the master compass to the repeaters, is driven by the large azimuth gear on the phantom element. The transmitter is attached to the lubber ring, and therefore the corrected compass heading is furnished automatically to the repeater compasses.

Azimuth Motor

The azimuth motor, which furnishes the power to keep the phantom element in exact alignment with the sensitive element, is mounted on the spider frame and geared to the large azimuth gear on the phantom element. It is a reversible, shunt motor, controlled through an amplifier panel by the signal from the pick-up transformer on the phantom ring. When the azimuth motor operates to correct for any misalignment of the rings, the inertia of the phantom element carries it beyond the center of alignment, initiating a signal opposite to that which started the system in motion. Therefore the azimuth motor is reversed, the reversal being continuous so that the phantom element never is completely at rest, but hunts or oscillates rapidly back and forth through an arc of about two tenths of a degree. The oscillation of the phantom element reduces the effect of friction about the vertical axis to a minimum. Oscillation is absent in the repeaters, a lost-motion device in the transmitter preventing it from being transmitted to the repeater cards.

NON-HUNTING COMPASS: Because of recent improvements in follow-up amplifiers, it is no longer necessary to introduce oscillation or "hunt" about the vertical axis. Consequently, on the latest Mk. XIV Compasses, which have the re-designed amplifiers, there is no visible hunt. The result is a smoother transmission to the repeaters and elimination of *all* lost motion.

The master compass exclusive of the binnacle is shown in Figures 24 and 25.

Binnacle

The binnacle supports and provides a protective housing for the master compass. The compass is suspended in the binnacle within a gimbal system so that it will hang vertically regardless of the ship's motion. The gimbal system is supported in the binnacle on flexible springs to prevent the vibration of the ship from being transmitted to the compass. The glass top cover and the doors in the sides of the binnacle may be opened or removed entirely to expose all parts of the compass for oiling, cleaning or inspection. Ordinarily the compass binnacle is kept closed and locked as shown in Figure 26.

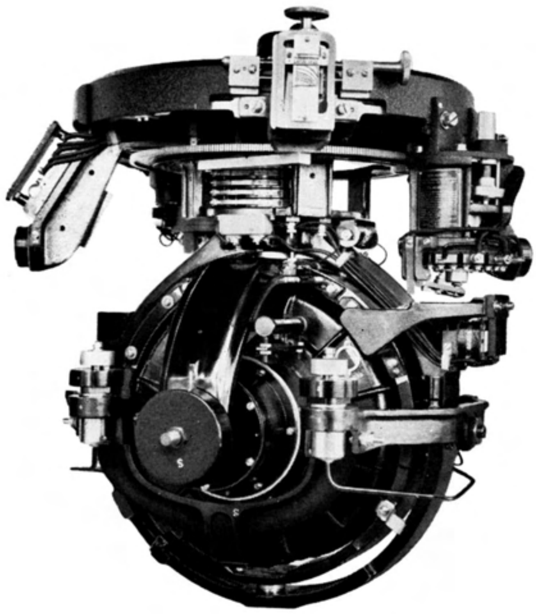


FIGURE 24.
Master compass, south view.

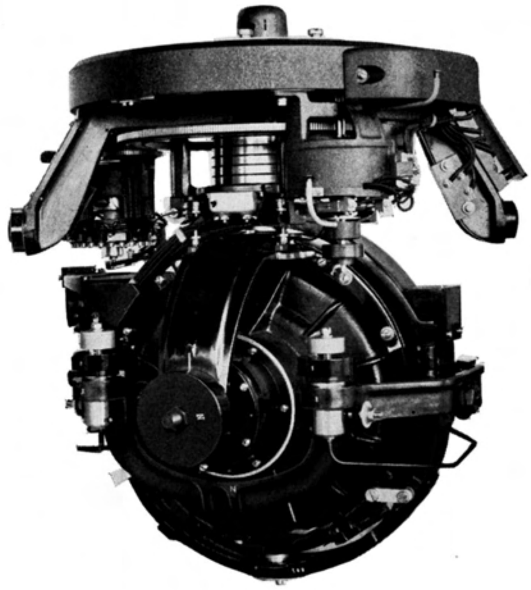


FIGURE 25.
Master compass, north view.

Electrical System of the Master Compass

The elements of the electrical system are shown in Figure 27. The ship's D-C. supply operates a motor-generator which provides 3-phase, 210 cycle, 50 volt current for spinning the compass rotor. Seventy volt direct current is obtained from the ship's supply through a carbon pile voltage regulator for operating the repeaters and the D-C. end of the motor-generator.

Electrical System of the Repeater Compasses

The electrical circuit of the repeater system is shown diagrammatically in Figure 28. The armature of the small motor on the right is geared to the card of the repeater compass. This motor has three pairs of field poles. These poles are connected to the commutator segments of the transmitter which is mounted on the lubber ring of the master compass. The roller brushes of this transmitter are driven by the azimuth gear of the phantom element. As the ship turns in azimuth relative to the master compass, these roller brushes move over the commutator segments and supply current to each of the three pairs of poles of the repeater motor in succession. The soft iron armature of the repeater motor therefore places itself between one pair of poles, then halfway between that pair and the next, then between the next pair, and so on, so as to turn the repeater

FIGURE 26.
Master compass binnacle.

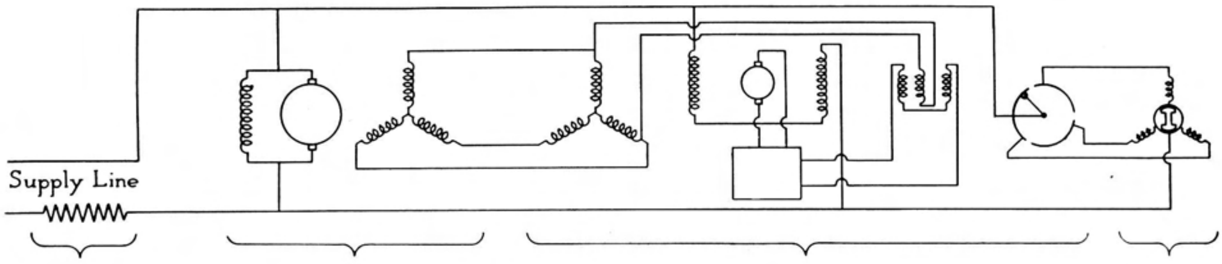


FIGURE 27.

Schematic diagram of the electrical circuits of the gyro-compass.

compass card to follow the master. Each step of the repeater is equivalent to 10 minutes of arc, or one-sixth of a degree, on the compass card.

In addition to the repeaters themselves, the Course Recorder and the Gyro-Pilot are also operated from the repeater circuit, as the activating elements of these instruments are repeater motors. The Course Recorder makes a graphic record on a printed chart of all changes of the ship's course, and shows the time when they take place. The Gyro-Pilot steers the ship. These two instruments will be described further on in this booklet.

AUXILIARIES AND ACCESSORIES

The switches for the operation of the compass rotor and the repeaters are contained on the control panel. The amplifier panel contains the switches for the operation of the follow-up system. It also contains the vacuum tubes, transformers and condensers and the electrical connections for converting the relatively small signal voltages induced in the pick-up transformer into sufficient power to energize the azimuth motor. A motor-generator converts the ship's D-C. supply into three-phase alternating current for spin-

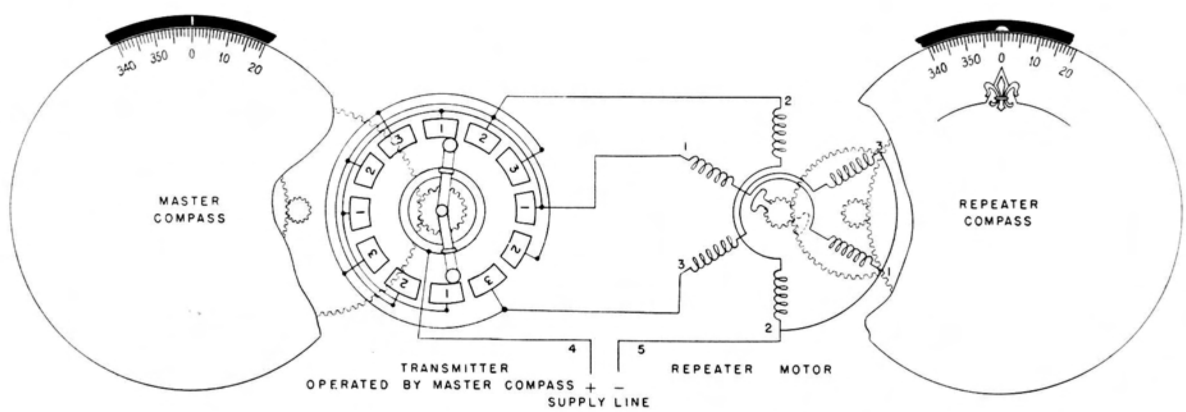


FIGURE 28.

Schematic diagram showing how the repeater compass is operated from the master compass.

ning the compass rotor. The auxiliaries, together with the master compass are usually installed in a special room where they may be kept clean and protected from the weather. An alarm unit or buzzer mounted in the wheelhouse provides a warning in case of failure of the compass or repeater circuits. Figure 29 shows a typical compass arrangement. A complete gyro-compass equipment usually consists of the master compass, as many pelorus or bearing repeaters as may be required, a steering repeater, direction-finder repeater, course recorder and Gyro-Pilot.

A schematic wiring diagram of the compass equipment is shown in Figure 30.

THE COURSE RECORDER

The importance of the course recorder can hardly be over-estimated. In everyday use it provides a visual check upon the quality of the steering, giving a permanent record of every angular movement of the ship's head at the time such movement takes place. Properly annotated, the course recorder chart supplements the ship's log, and the owner, who cannot afford to gamble with fog, reefs and shoals, is afforded a further safeguard as his valuable property moves from one place to another in pursuit of profitable cargoes. Many times the course recorder has been the deciding factor in collision cases and has saved the owners thousands of dollars in costly litigation.

When automatic steering through the gyro-pilot is employed, the course recorder shows graphically when the best steering is obtained and by this means the "weather" and "rudder" adjustments on the gyro-pilot can be set to secure the most accurate results for any set conditions.

Description

The course recorder (Figure 31) is a complete unit operating on the repeater circuit from the master compass. It comprises a repeater motor which drives the controlling mechanism for an indicator dial and a pair of ink pens. A clock-controlled drive roller feeds a paper chart under the pens at the proper rate, and a spring-driven re-wind roller winds up the paper and keeps it taut. The action of the re-wind roller is similar to that of an ordinary window shade, except that an automatic lock is provided on the spring drive to guard against excessive speed.

The mechanism is shown in Figure 32. The repeater motor shaft extends in both directions, each shaft end carrying a worm. The upper worm drives the indicator dial, while the lower worm drives a cam cylinder. The cylinder has a groove which causes a trolley, carrying the course pen, to travel horizontally so that the course pen matches, on the paper chart, the position of the indicator dial. The dial periphery constitutes a cam which causes the zone pen to shift from one zone to another, on the paper chart, according to the dial position.

The clock mechanism is enclosed in a metal casing from which the necessary winding stems and control knobs protrude, at the left.

The recorder chart is a specially printed sheet of paper 90 feet long, sufficient for a continuous record of 30 days.

A window is provided in the front cover to enable an observer to examine several hours of record without opening the instrument. An

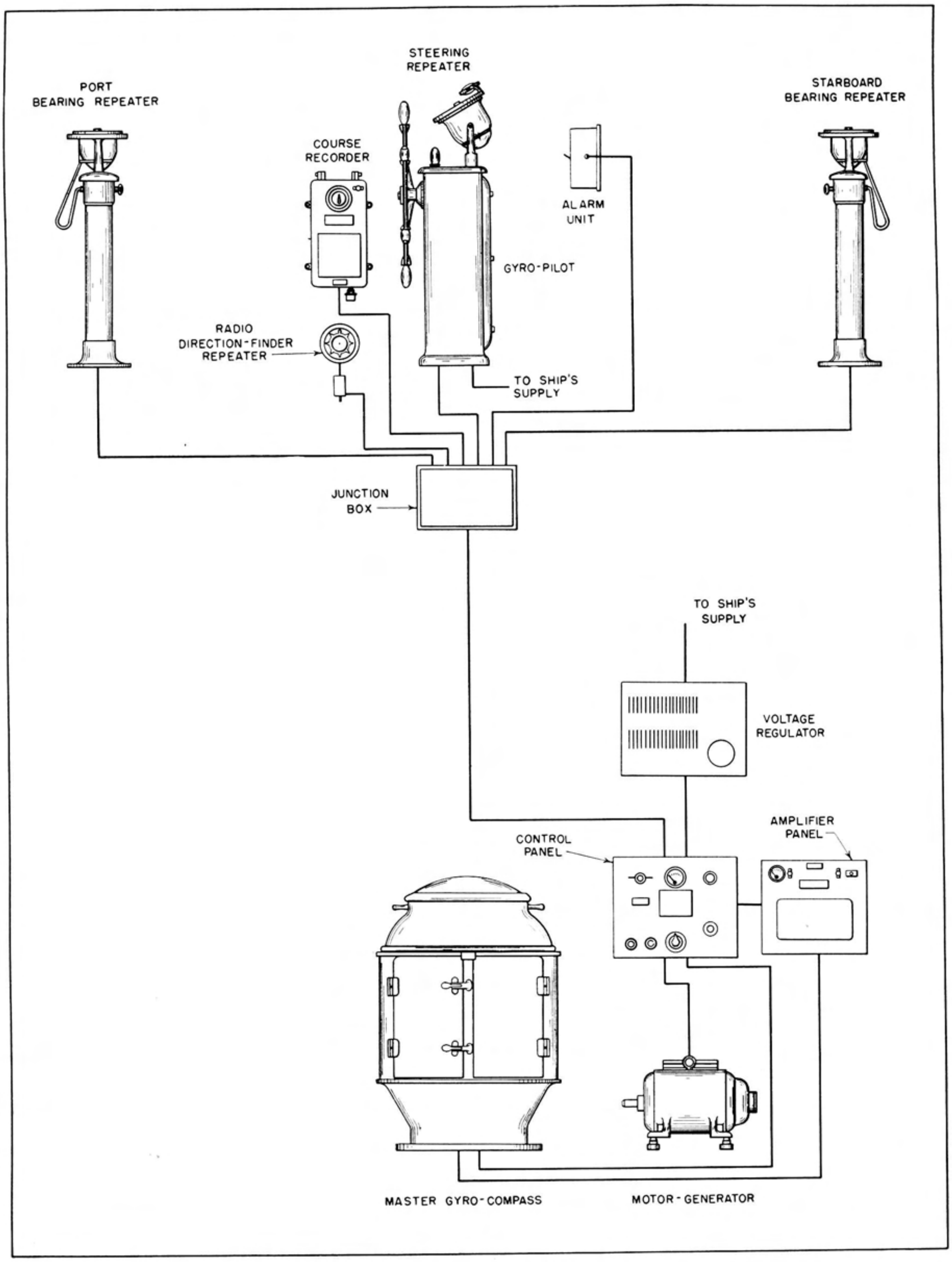


FIGURE 29.
Typical compass arrangement.

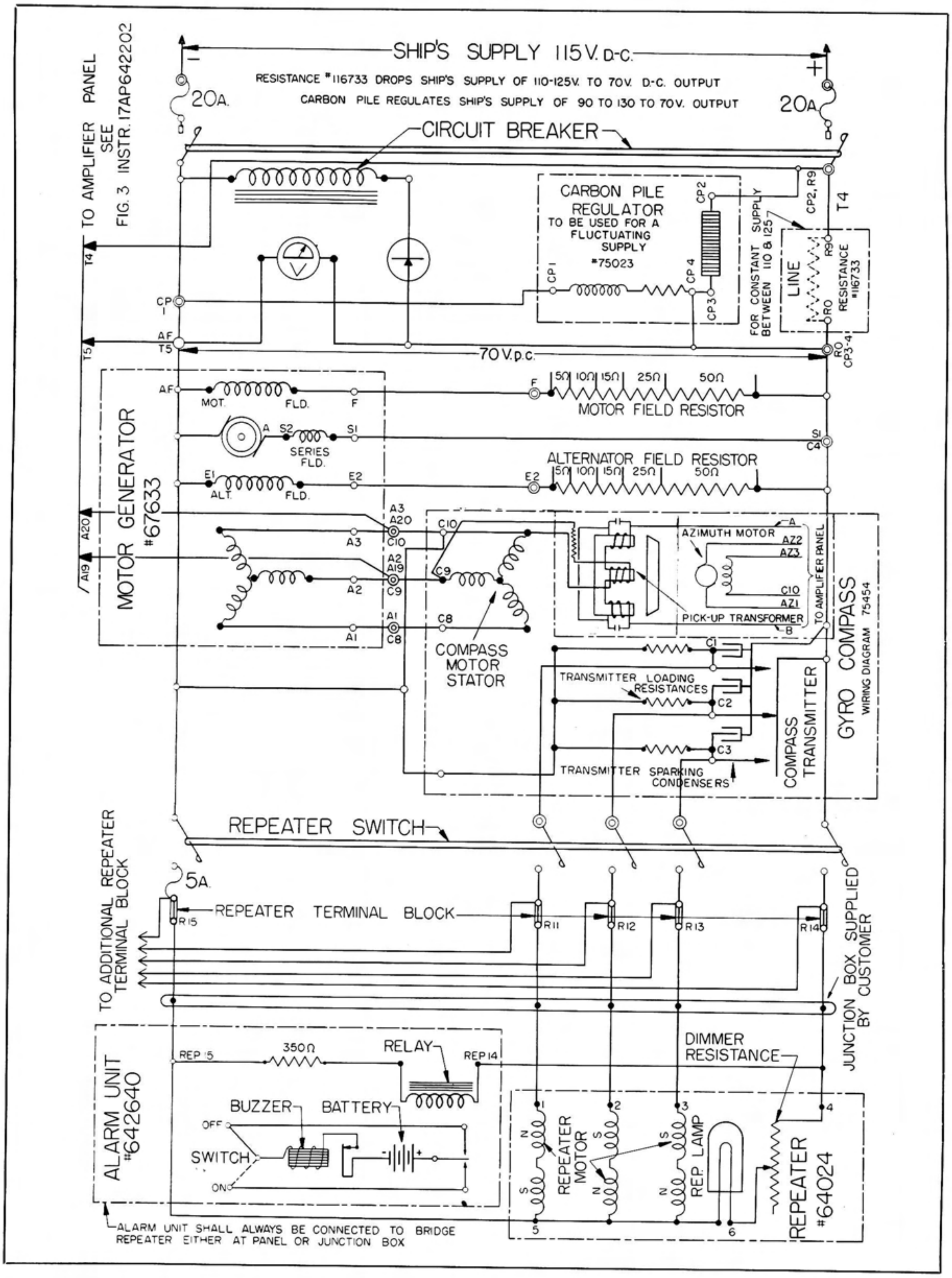


FIGURE 30.

Schematic wiring diagram.

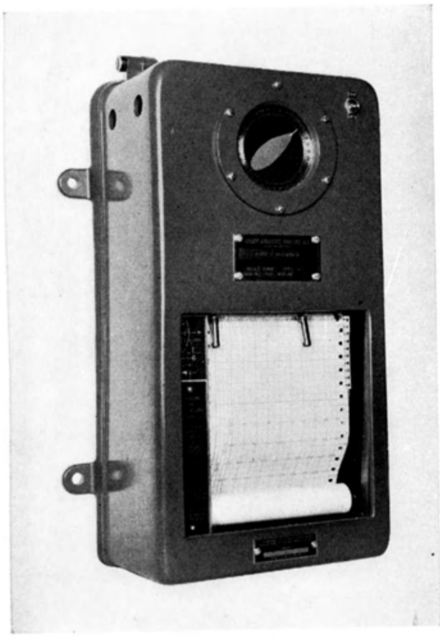


FIGURE 31.
The course recorder.

auxiliary indication of the ship's heading is also provided, when the cover is closed, by an azimuth scale concentric to the motor-driven indicator dial within.

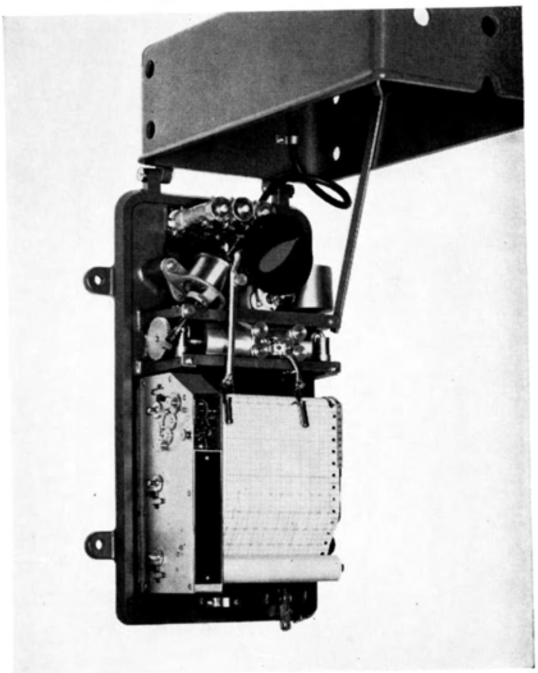


FIGURE 32.
Mechanism of the course recorder.

A lamp, controlled by a switch on the upper right corner of the front cover, provides illumination for reading the chart at night.

A wiring diagram for the instrument is shown in Figure 33.

Use of the Record

The operation of the course recorder requires no special training, all of the directions necessary being contained on an engraved instruction plate on the front of the instrument. The point that should be impressed upon the reader is the importance of keeping the record properly.

In order to augment the value of the record, notations should be entered liberally on the chart in regard to alterations of course, weather conditions, wind — anything, in fact, which tends to affect the steering of the ship. If steering automatically by gyro-pilot, the weather and rudder adjustments should be noted on the chart, and also the nature of the sea, whether moderate, rough, beam sea or head sea. The recorder clock should be checked every watch and the error, if any, noted on the chart.

Course changes of themselves have little significance unless the exact time at which they took place is known. The more important the event, the more necessary it is to pin it down to a definite time. The course recorder clock cannot be expected to operate as accurately as a ship's chronometer, and for this reason care is required on the part of the officers to see that it is set correctly or that any discrepancy is noted.

The time factor in connection with the course record can be of the utmost importance if it should ever be necessary to use the course recorder chart as evidence in case of accident, collision or stranding. If there were any difference between ship's time and course recorder time, this difference would have to be proven to the satisfaction of the court or else the record would be of no value as evidence.*

* A recent collision case hinged on just such a discrepancy in time. This case is described, with extracts from the court records, in a publication of the Sperry Gyroscope Company. It is available for those who wish to learn how course recorder records are used in court.

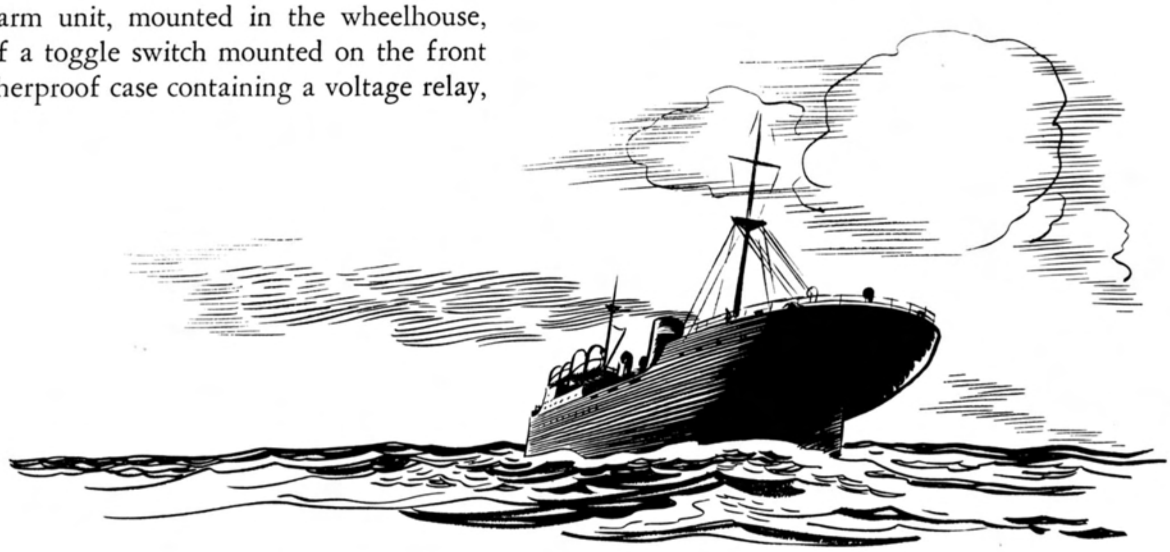
finder, or in other cases a repeater motor is supplied to the direction-finder manufacturers, who build it into their set. In some cases, where it is not practical to incorporate a repeater in the direction-finder, a repeater compass from which the ship's heading can be read is mounted alongside the direction-finder apparatus.

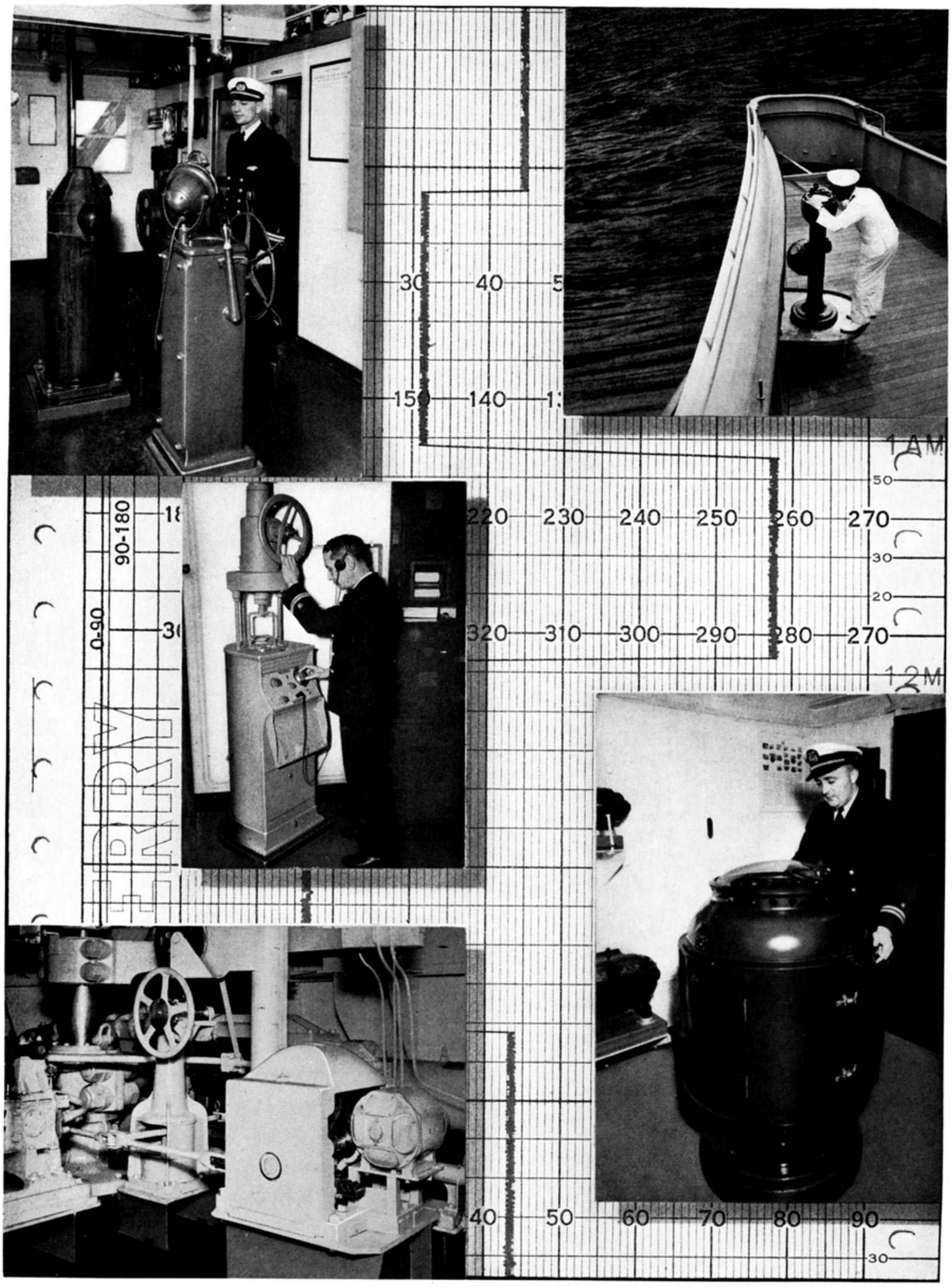
Just as the use of a bearing repeater increases the celerity and accuracy with which bearings and sights may be obtained, so too does the use of a repeater compass improve the effectiveness of the radio direction-finder. When using a bearing repeater, only the sense of vision is required; but when using a direction-finder, the operator depends upon his sense of hearing as well as his sense of vision. If only a dummy card is used, he must first set the card to the ship's course and then correlate the sound input of the receivers with the ship's heading, as verbally transmitted to him by the helmsman, and note the reading on the card. Before this can be done the ship may have yawed several degrees off the course, appreciably affecting the results. With a gyro-compass repeater under the direction-finder index, the card is always kept accurately set to true north, enabling the operator to make his reading at his own convenience without the necessity of cooperating with a second party.

ALARM UNIT

The alarm unit, mounted in the wheelhouse, consists of a toggle switch mounted on the front of a weatherproof case containing a voltage relay, a buzzer, and a set of dry cells which supply current for operating the buzzer. The relay is connected across the 70-volt supply to terminals 14 and 15 of the repeater circuit on the bridge. When the compass supply is normal, the relay armature is held in place by the energized magnet coil. The circuit to the buzzer is controlled by the toggle switch, which ordinarily is turned so as to silence the alarm.

Failure or reduction of the compass supply voltage or opening of a repeater switch causes the relay armature to drop, closing the buzzer circuit and sounding the alarm until the buzzer switch is turned off to silence it. To prevent the switch from being left in the OFF position when the supply has been restored and the relay armature returned to its normal operating position, the switch is so arranged that the buzzer is again sounded when the armature is in the normal position. The switch is then turned ON which silences the buzzer during normal operation.





Upper Left: Gyro-Pilot Control Unit, MS *Mooremacdove.* Upper Right: Bearing Repeater, SS *Mauretania.* Center: Radio Direction-Finder with Repeater Compass, MS *Dona Nati.* Lower Left: Gyro-Pilot Power Unit, Tanker *Esso Bayonne.* Lower Right: Master Gyro-Compass SS *America.*