REPORT No. 131

AERONAUTIC INSTRUMENTS
SECTION VII

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AERIAL NAVIGATION AND NAVIGATING INSTRUMENTS

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SECTION VII

AERIAL NAVIGATION AND NAVIGATING INSTRUMENTS

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Bureau of Standards

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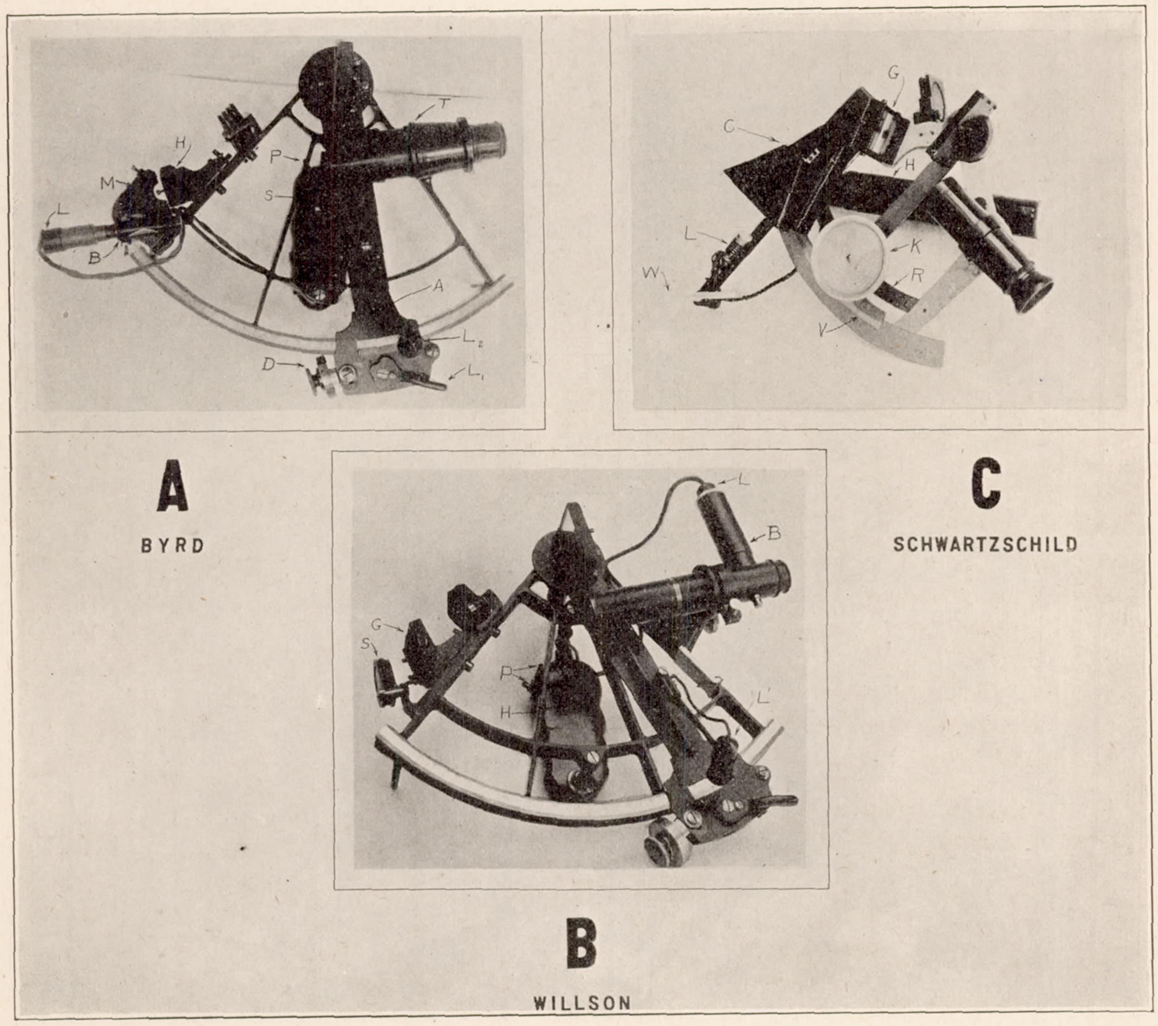

FIG. 16.—Bubble sextants.

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REPORT No. 131.

AERIAL NAVIGATION AND NAVIGATING INSTRUMENTS.

By H. N. Eaton.

SUMMARY.

This report is Section VII of a series of reports on aeronautical instruments (Technical Reports, Nos. 125 to 132, inclusive) prepared by the Aeronautic Instruments Section of the Bureau of Standards under research authorizations formulated and recommended by the Subcommittee on Aerodynamics and approved by the National Advisory Committee for Aeronautics. Much of the material contained in this report was made available through the cooperation of the War and Navy Departments.

The methods of marine and aerial navigation are fundamentally the same and the development of the latter has involved no new general principles. Differences in the conditions encountered on the ocean and in the air and the widely different characteristics of the craft involved in the two cases have necessitated the modification of the methods and instruments used in marine navigation, as well as the development of special instruments, to meet the requirements of aeronautics.

This paper outlines briefly the methods of aerial navigation which have been evolved during the past few years and describes the instruments used.

Dead reckoning, the most universal method of navigation, is first discussed. Then follows an outline of the principles of navigation by astronomical observation; a discussion of the practical use of natural horizons, such as sea, land, cloud, and haze, in making sextant observations; the use of artificial horizons, including the bubble, pendulum, and gyroscopic types; and a description of the rapid methods and the special instruments which have been devised to expedite the reduction of observations and the plotting of position. Lastly, the comparatively recent development of the radio direction finder and its application to navigation are discussed.

INTRODUCTION.

Until the beginning of the recent European war, aerial navigation in a scientific sense had received comparatively little attention. A limited amount of work along these lines had been done, but comprehensive methods for overcoming the difficulties peculiar to the navigation of aircraft had not been developed.

Perhaps the most conspicuous example of the use of this new art prior to 1914 is to be found in the celebrated attempt of Wellman and Vaniman to cross the Atlantic Ocean with the dirigible *America* in 1910. On this voyage a sextant with an artificial horizon was used for the absolute determination of position, while methods of measuring the air speed, ground speed, compass course, and angle of drift provided the necessary data for computing the dead reckoning position of the ship.[1] The methods of navigation used on this flight were very similar to those which are coming into use to-day. The most noticeable difference was the absence of the radio compass and the turn indicator.

During the war the art of navigating aircraft was developed somewhat, principally owing to the attempts at long-distance bombing. The British found it possible, after considerable

[1] "The Aerial Age," Wellman.

work at Oxfordness, to arrive within 5 or 6 miles of their objective after flying above the clouds for approximately 100 miles. The Germans in their Zeppelin raids on England were but partly successful in their navigation, for they managed to reach their objective yet often failed to return to their base, owing to the almost insuperable difficulties encountered in flying long distances at night with uncertain information as to weather conditions.

The war demonstrated the value of aerial supremacy beyond all question. The development of commercial aviation is the most promising means by which the heavy cost of aeronautical progress can be at least partially defrayed. Commercial aviation in turn depends to a great extent upon the solution of the difficulties encountered in aerial navigation. Not until aircraft are independent of all but the most extreme weather conditions, not until they can be flown for hundreds of miles without sight of the ground and still come out within 15 or 20 minutes flying time of their objective, not until forced landings in fog cease to be a source of serious danger will this means of transportation be suitable for commercial use.

Unfortunately, only a beginning has been made toward solving the problems of flying and landing in fog. The turn indicator has relieved cloud flying of its greatest danger, but landing from an uncertain altitude on a spot which is invisible from the air is still a dangerous undertaking. In all probability the solution will be found not only in additional instrumental aids to navigation but also in the utilization of information transmitted by wireless from a well-organized and widely distributed meteorological service provided for the assistance of the aerial fleets.

AERIAL NAVIGATION METHODS.

The reason that present-day methods of aerial navigation were so well established during the earliest days of aeronautics is probably due to the close analogy between aerial and marine navigation. A ship travels through the water on a given course at a known speed, while at the same time the ocean currents and the wind carry it from its course by an amount which is usually quite accurately known also. The position of the ship at any instant can be computed with a considerable degree of accuracy by dead reckoning and checked occasionally by astronomical observation. The aircraft flies at a known speed on a given course through the air. At the same time the winds sweep it from the course steered by an amount which, under favorable conditions, is known. The aviator can thus determine his position by dead reckoning and occasionally check it by observation on the sun or a star just as is done in marine navigation.

Here the analogy ends, and in the remaining considerations the disadvantage lies almost wholly with the aircraft. In spite of certain advantages which are unique to flight, the higher rates of speed of the craft and of the supporting medium, the impossibility of charting the winds as the ocean currents are charted, the dangers of landing in fog or darkness, and the added difficulties due to the fact that we have three dimensions involved instead of two, all tend to make the navigation of aircraft more difficult and hazardous than navigation on the sea. This entails the development of new methods and instruments for aerial use as well as the modification of those already in existence.

The methods of aerial navigation which stand out prominently are three in number: "Dead reckoning," "astronomical observation," and "directional wireless telegraphy," if we omit (1) the common practice of flying by map, consisting simply of steering one's course by means of objects on the ground which can be identified on the map, and (2) the possible use of a gyroscopic device for indicating latitude and longitude. Several attempts have been made to construct such an instrument, but it is extremely doubtful whether in the present state of development of gyroscopic apparatus sufficient accuracy can be attained in this way.

No one method or combination of methods has been found preeminently suitable for exclusive use under all conditions. What might be well suited for a transatlantic flight would not be adapted to use on a cross-country trip of a few hundred miles. Lighter-than-air and heavier-than-air craft each have their own characteristics which involve different variations of the fundamental methods of navigation.

DEAD RECKONING.

Of the three fundamental methods of navigation, that by dead reckoning is unquestionably the most universally used. It is always required in some form, however simple, even when reliance is placed on one or both of the other methods. Although dead reckoning may be partly superseded by the radio direction finder, it can never be dispensed with entirely.

Navigation by dead reckoning consists in determining the position and course of any craft from its known or estimated direction and speed over the surface of the earth. In aerial navigation the direction in which the craft is heading and its speed relative to the air can be found with comparative ease, but unfortunately for simplicity, the winds are usually present to complicate the problem. In nearly every case this means that both the speed and the direction of motion with respect to the ground differ from that shown by the air-speed indicator and the compass. If the direction and the speed of the wind are known, the problem still remains simple, involving merely the solution of a velocity triangle; but the wind is rarely known accurately at the start of a flight and only too often no information is available. In this case the navigator is forced to rely on observations which he can make while in the air to give him a knowledge of the drift caused by the wind.

In time a more intimate knowledge of the atmosphere and a well-organized meteorological service will undoubtedly serve to give aviators more complete and accurate data to aid them in their navigation, but even then it will still be necessary to check the course actually followed by means of drift and ground speed observations.

From what has been said, it can be seen that the measurement of four different quantities—heading, air speed, ground speed, and drift—may be involved in navigation by dead reckoning. For the purposes of this paper the instruments used in measuring these quantities and in reducing them to useful form may be classified as (*a*) Direction Indicators; (*b*) Speed and Drift Indicators; and (*c*) Computers and Plotting Accessories.

USE OF DIRECTION INSTRUMENTS.

COMPASSES.

The determination of direction is the most fundamental process in navigation. A knowledge of his speed may not be absolutely essential to the navigator, but without the sense of direction he may be completely lost. Aside from the limited possibilities of directing one's course by map, by rough measurement of angles from the sun or stars, or by the aid of the radio direction finder, the compass is an absolute necessity to navigation, whether aerial or marine.

Owing to its supreme importance, this instrument had already been brought to a high state of development for marine use before the days of modern aviation. Its first applications to aerial use, however, showed that an entirely new development was needed before it would function properly in aircraft. It was not simply a question of reducing the size and weight of the instrument but of altering the design radically, in order to make the compass function properly when subjected to the severe conditions found in aviation.

It had already been learned that the dry compass ordinarily used on shipboard was unsuitable for small boats where the rolling and pitching in bad weather and the engine vibrations were very pronounced. Under these conditions the compass card was found to lose its stability and to oscillate in both horizontal and vertical planes, the amplitude often increasing until continuous rotation about the vertical axis resulted. Furthermore, the vibration damaged the pivot point, and an increase in pivot friction resulted which made the error of the instrument still greater. These considerations led to the adoption of the liquid compass for small boats. The marked similarity between the conditions encountered here and those met with in the air explain the almost universal adoption of this type of compass for aerial work.

The liquid in the bowl serves a double purpose: It damps the motion of the card, reducing the oscillations and thus improving the stability; and it removes a portion of the weight on the pivot point and so tends to preserve the latter, owing to the reduction of the intensity of the shocks given it. The decrease in the apparent weight of the card is also beneficial in that it reduces the pivot friction.

Inseparable from the advantages due to the liquid are several disadvantages. The liquid serves as a damping medium, but it also forms a viscous connection between the bowl and the card, and when the former turns the latter is dragged around, too. The same property of the liquid makes the compass sluggish, with the result that it responds but slowly to changes of direction.

In adapting the liquid compass to aerial use a number of modifications were made, the most important of which was probably the adoption of a short period. The period of the marine compass is in the neighborhood of 50 seconds, and experience in the air brought protests from the pilots that a compass having so great a period took too long to come to rest after a turn. Consequently compasses having a period of from 10 to 20 seconds were adopted. Other changes included the use of stronger magnetic moments in an attempt to overcome the sluggishness produced by the liquid and the attaching of the pivot to the card instead of the bowl in order to reduce the turning effect due to vibration.

During the early days of its use the peculiar action of the short-period compass caused the instrument to fall into discredit. It was found that on banked turns from northerly courses the compass swung wildly and often indicated a turn in the wrong direction. A study of this "northerly-turning error," as it was called, led to the temporary adoption of a long-period compass in an effort to reduce the effect.

Errors of compasses.—The compass, as used in aerial navigation, is subject to errors due to (*a*) calibration, (*b*) pivot friction, (*c*) permanent magnetism of the craft, (*d*) induced magnetism, (*e*) vibration, (*f*) tilting of the card, (*g*) linear acceleration of the craft, and (*h*) turning of the craft.

(*a*) and (*b*) The sum of the calibration and pivot friction errors should not be greater than about 2° in a good compass, such as is needed for navigation. The friction error can be reduced to a very small amount by keeping down the weight of the card. These errors are discussed in Part III of Report No. 128 of this series.

(*c*) The deviation due to permanent magnetism is caused by the fact that the steel used in the construction of the airplane acquires a certain amount of permanent magnetism due to vibration and shocks. The field thus set up lies in a general way along the longitudinal axis of the ship. The deviation caused by this field changes sign when the aircraft changes its azimuth by 180°; hence it is called the "semicircular deviation." The permanent magnetism thus produced is not constant over an extended period owing to the vibration and shocks incidental to the use of the ship.

(*d*) The earth's field induces magnetism in the soft iron of the craft, producing a field which varies in direction as the azimuth of the airplane is altered. This field causes a deviation which changes in sign for each change in azimuth of 90°, so the name "quadrantal deviation" is applied to it.

The deviations due to the causes just discussed can be largely eliminated by "swinging the airplane" and compensating the compass.[2] The semicircular deviation, the more important of the two, is corrected by heading the craft successively north, east, south, and west and reducing the deviations found in this way to the smallest possible amounts by the use of small compensating magnets. The quadrantal deviations are corrected by heading the airplane successively northeast, southeast, southwest, and northwest and reducing the deviations found in these directions to a minimum by means of two soft iron spheres properly placed. After this process has been completed the airplane is "swung" again and the remaining deviations are found for the points of the compass. A table of these deviations can then be prepared for use when flying. Owing to the change in the permanent magnetism of the ship, the semicircular deviation should be compensated at frequent intervals.

The errors which have been considered above can be determined fairly well and corrected under ordinary conditions. On short flights or on flights over territory which is known and visible they are not very important, as the course can be corrected at frequent intervals. On

[2] "Aerial Navigation," by J. E. Dumbleton.

long flights and particularly on transoceanic flights the accuracy of the compass is of supreme importance, however. A glance at the map of the Atlantic Ocean will emphasize at once the accurate navigation which would be required to enable a craft flying, say, to the Azores to attain its objective. An error of 2° in following the true course might cause it to miss its destination with the chances greatly in favor of its continuing on into another vast expanse of ocean.

The errors which remain to be discussed can not be accurately determined and compensated as can the others, although they can often be reduced in amount. The error caused by the electrical circuits in the engine is a good example of this. This disturbance may be serious if the compass is near the engine, but it may be overcome by removing the compass from the field thus set up.

(*e*) Rotary vibration in a horizontal plane has a very serious effect upon compasses in which the pivot is fastened to the bowl and the cup is fastened to the card. Under the influence of such vibrations the pivot will carry the card around in the direction of the vibration. In tests carried on at the Royal Aircraft Factory with a British Admiralty standard compass,[3] deviations due to this cause were found to range from 7° at 1,400 R. P. M. to 42° at 1,600 R. P. M. Reversing the positions of the pivot and cup reduced this deviation to 1° at 1,100 R. P. M. and 4° at 1,600 R. P. M.

The suspension of the bowl was also carefully investigated at the same time. It was concluded after extensive tests that rubber stops, unless they are too loose to maintain the proper direction of the bowl with respect to the case, do not damp out excessive vibrations. Spring mountings were also found unsatisfactory owing to resonance at certain speeds. The method finally adopted was to support the bowl on a polished plate with a felt pad between the two. Flat leaf springs mounted on the case supported the bowl and maintained its direction but allowed it to slide on the felt.

When a compass with the standard arrangement of pivot and cup and with this mounting was tested in an airplane on the ground with the engine running, the deviation due to vibration was reduced to a maximum of 2° at 1,600 R. P. M. The results obtained improve rapidly as the distance of the compass from the engine increases. This is due both to a reduction of vibration and to a lessening of the effect of the engine circuits.

(*f*) If the axis about which the card rotates is inclined to the vertical while the craft is flying a straight course, a large error in the compass reading may be introduced. This is due to the vertical component of the earth's magnetic field, which then tends to rotate the card about its axis.

(*g*) Linear accelerations of the aircraft while flying a straight course other than magnetic north or south produce an error in the compass reading. Owing to the mass placed on the south side of the card to balance the force due to the vertical component of the earth's magnetic field, the center of gravity of the needle does not lie in the vertical line through the point of support. A linear acceleration produces a moment acting about the point of support to deflect the needle.

(*h*) Perhaps the most difficult error to contend with and the one that has had the most serious consequences is the "northerly turning error," which occurs when the aircraft veers from a northerly course. The short-period compass under such conditions deviates widely from the correct reading, and, what is worse, often indicates a turn in the opposite direction to that which is actually being made. When this occurs in a cloud or in a fog, the results are likely to be disastrous, for the pilot loses all sense of the horizontal under these circumstances and must depend on his instruments to keep the ship in equilibrium.

It is possible to derive the equation of motion for the compass card for specified turns from a given course.[4] In its general form this equation can not be integrated, but, by keeping the values of the variables sufficiently small, approximations can be made which allow the integration to be performed. Thus it is possible to investigate the initial motion of the compass

[3] "Report on the Errors of Compasses on Aeroplanes," by Keith Lucas, British Advisory Committee for Aeronautics, vol. 7, 1915–16, p. 554.

[4] Report of the British Advisory Committee for Aeronautics, "The Northerly Turning Error of the Magnetic Compass," F. A. Lindeman 1916–17, pp. 678–698.

in a turn from the north, for example, and a large turn can be investigated by a step-by-step process, keeping the variables small for each step.

It is usually assumed that the liquid does not rotate with the bowl during a turn. This of course, is not true, even with a spherical bowl such as is used in the R. A. F. Mark II compass. The condition for rotation of the liquid with the bowl can be put into the equation of motion and its effect thus determined. The true state of affairs must lie between these two extremes, and this has been corroborated by actual tests.

The cause of the "northerly turning error" is discussed in Part III of Report No. 128 of this series.

The development of the turn indicator has made it possible to neglect the compass entirely during the turn. The latter can now be utilized in its proper rôle, that of giving the direction of a straight course, while the former can be used exclusively for turns.

A detailed description of the different compasses in aerial use will be found in Part IV of Report No. 128 of this series.

TURN INDICATORS.

While aerial navigation in a strict sense may consist simply of the geometrical problems involved in flying from one point to another, in a broader sense it may be considered to include other problems which are essential to carrying out the flight from a practical standpoint, such as the determination of the radius of action or the ability to fly through fog. Commercial aviation will never be a success, however accurately courses and distances can be determined, so long as the craft is likely to fall out of a cloud in a tail spin, owing to the inability of the pilot to keep his equilibrium.

Before the turn indicator was developed it was an all too common experience for the pilot upon entering a cloud to notice the compass needle beginning to swing. This meant that the airplane was turning and he would immediately try to correct the course. With all sense of the horizontal lost, all he could do, however, was to adapt his bank to the turn, since the usual type of banking indicator gives only the apparent vertical. So he would get onto a sharper and sharper turn, particularly if turning from the north with a short-period compass. The airspeed would now creep up and, in correcting this, he would stall the machine, which would then fall out of control until a view of the ground enabled him to regain his balance and level off or until he crashed. A conspicuous example of such an occurrence is to be found in Sir Arthur Whitten Brown's "Flying the Atlantic in Sixteen Hours," page 59.

With a turn indicator in front of him, the pilot can recognize a turn as soon as it commences and can correct it. The banking indicator will then give the true vertical and the ship can be kept on an even keel and flown in a straight line.

Turn indicators are described in Part V of Report No. 128 of this series, so brief reference only will be made to them here.

The static head turn indicator.—This turn indicator consists of two static pressure nozzles mounted one at each end of the wings of the airplane and connected to opposite sides of the diaphragm of a very sensitive pressure gage. When the airplane banks for a turn, the two static nozzles are at different elevations, and consequently are at points of different static pressure. Without discussing the other forces acting upon the pressure indicator, since the subject is thoroughly treated elsewhere in this report, it will be said that the resultant force upon the diaphragm may be considered due to the difference in barometric pressure between the levels of the static nozzles or due to the centrifugal force of the air in the tubes connecting the indicator to the static nozzles. The differential pressure acting upon the indicator is thus a measure of the rate at which the aircraft is turning. The Darwin static head turn indicator is the only instrument of this type in common use.

The gyroscopic turn indicator.—The operation of this type of turn indicator is based on the action of a gyroscope. If the axis of spin is fore and aft, the precession then takes place about an axis parallel to the lateral axis of the ship. Springs limit the precession to a small amount and the deflection is magnified and read on a dial.

A number of gyroscopic turn indicators have been developed. In most cases the gyro wheel is in the form of an air turbine which is driven either by the blast of the air stream or by the suction developed by a Venturi tube mounted on a wing. In some cases an electrical drive is used.

Errors of turn indicators.—The static pressure turn indicator works well under favorable conditions if properly mounted. It has, however, several serious defects. (*a*) The instrument is said to read lateral accelerations almost independently of the bank. Thus it is liable to be in error whenever side-slipping occurs. (*b*) Obviously the differential pressure involved is extremely small. This makes a very delicate indicator necessary and increases the liability to error due to local pressure disturbances. (*c*) It has an excessive lag. (*d*) Under bad weather conditions the nozzles may freeze up solid and the instrument will cease to function.

The best gyro turn indicators with an adjustment for sensitivity are unquestionably more satisfactory than the static pressure type of instrument. They are practically instantaneous in action, can be adjusted to the desired sensitivity, start functioning again immediately after the plane has been stunted, and can be made strong and rugged, owing to the large forces involved.

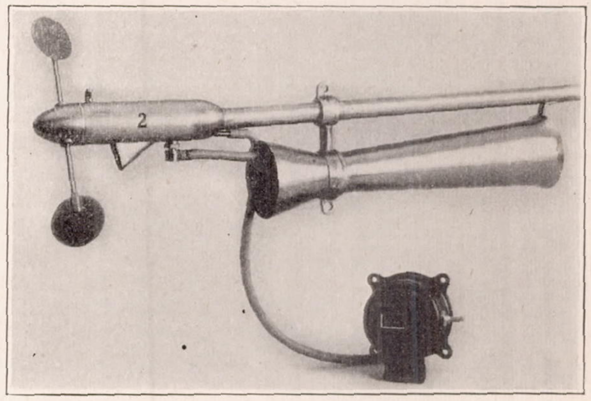

FIG. 1.—Pioneer air-distance recorder.

USE OF SPEED INSTRUMENTS.

Under this heading are included air-speed indicators, ground-speed indicators, and drift indicators.

AIR-SPEED INDICATORS.

Little will be said of air-speed indicators in this paper. The instruments are well known, forming a standard part of the equipment of all aircraft, and have been treated thoroughly in other parts of this report. The reader is referred to Parts I and II of Report No. 127 of this series, also National Advisory Committee for Aeronautics Report No. 110, "The Altitude Effect on Air-speed Indicators," by M. D. Hersey, F. L. Hunt, and H. N. Eaton.

PIONEER AIR-DISTANCE RECORDER.

This instrument (fig. 1) is designed to record the air distance traveled. A small propeller is mounted on one of the forward wing struts. This propeller makes a definite number of revolutions for each mile of air which passes it, and at the end of each mile operates a valve which admits the suction created by a Venturi tube to the recorder, thus operating pneumatically the mechanism which adds 1 mile to the reading. Since the propeller has very little resistance to its motion, the apparatus is very nearly independent of the density of the air. The makers claim that the maximum error of the instrument due to the change in air density is less than 1 per cent at 20,000 feet.

GROUND-SPEED INDICATORS.

The two principal types of ground-speed indicators which have been developed for use on aircraft are based upon optical and dynamical principles. The optical type is used to follow and measure the relative motion of objects upon the ground with respect to the aircraft and so is dependent upon the visibility of the ground from the craft. The dynamical type integrates the accelerations of the aircraft, and consequently is independent of visibility. A discussion of the principles upon which the various types of ground-speed indicators are based is to be found in Part III of Report 127 of this series.

While the measurement of ground speed is a distinct operation, practically it is often convenient to combine the optical ground-speed indicator, the most commonly used type, with a drift indicator owing to the fact that in this type of ground-speed indicator the angle of drift is found, whether or not it is read. On this account the description of drift indicators which follows will include descriptions of several simple ground-speed indicators of the optical type.

THEORY OF DRIFT MEASUREMENT.

Just as in marine navigation it is necessary to take into account the speed and direction of ocean currents in order to follow a given course, so in aerial navigation the motion of the supporting medium relative to the earth must be considered. And in the latter case the difficulties involved in taking full account of the motion of the medium are immensely greater. Not only are the velocities of the winds many times those of the ocean currents, but they are changeable, varying from day to day, and even from hour to hour. Unlike ships, which are limited to motion upon the surface of the sea, aircraft often fly at elevations differing by several miles, and it is a well-known fact that the winds usually vary both in amount and direction with altitude. It is probable that meteorological information will in time reach such a state that the conditions which the aviator will be likely to meet in a given flight can be predicted quite accurately in advance, but it will never be possible to chart the winds as the ocean currents are charted.

The value of meteorological data for commercial aviation can hardly be overestimated. By choosing his altitude properly, the aviator can often obtain a favorable wind in both going to and returning from his objective. The lack of such information may often add greatly to the time of his flight and, if visibility is poor, he may be swept miles from his course. A historic instance of such an occurrence is that of a fleet of Zeppelins which, after a raid on England on October 19, 1917, ascended into an air current very different from that existing at the lower levels. The crews of the dirigibles, not knowing of this change in the wind, made a wrong allowance for its effect, with the result that the ships were swept over France, where a number of them were destroyed.[5]

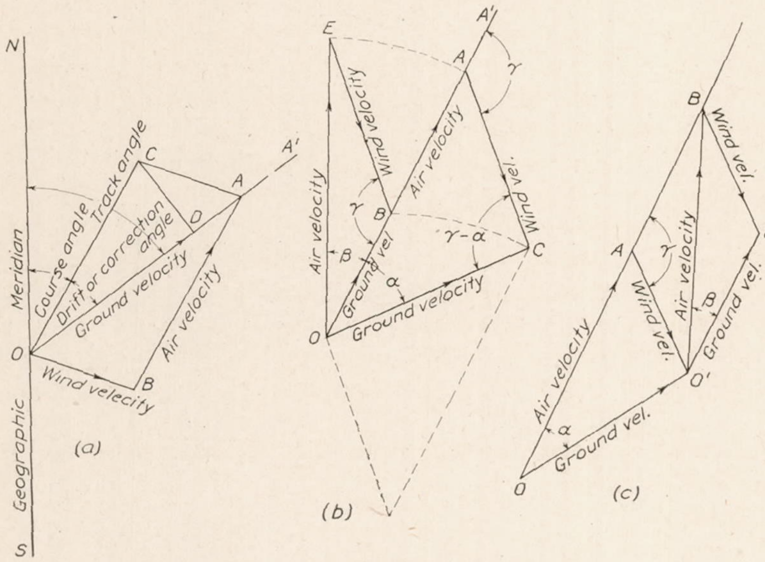

Fig. 2.—Drift diagrams.

The fact that the wind usually alters the compass course which should be steered to reach a definite point on the surface of the earth makes it necessary to determine the angle by which the heading of the plane must be altered in order to follow a particular course over the ground. The fundamental problem involved in all cases is the determination of enough quantities to solve the velocity triangle whose sides represent in amount and direction the air speed, wind speed, and ground speed.

In figure 2(*a*) the triangle (OAC) represents the velocities involved. Suppose the aircraft starts from (O) to reach a point (A′). The angle (NOA′) which the course to be followed makes with the geographic meridian can be determined from the map. This will be called the "track angle" and the course (OA) which the aircraft actually follows over the ground will be called the "track," or the "course-made-good," in accordance with customary usage. The wind is

[5] Manual of Meteorology, Part IV, page 73. "The Relation of Wind to the Distribution of Barometric Pressure," by Sir Napier Shaw.

represented in amount and direction by the vector (OB). Let us assume that (OB) represents the distance which the wind moves in unit time. Now, if we take (B) as center and with a radius equal to the distance which the craft moves through the air in unit time swing an arc cutting the straight line from (O) to (A′), we obtain point (A) which represents the point which the aircraft can reach in unit time if so headed as actually to fly over the ground from (O) toward (A′) in a straight line. Now, drawing (OC) parallel to (BA) and (CA) parallel to (OB), we have the triangle of velocities which is to be solved. Knowing (OC), (CA), and angle (OAC), it is a simple matter to solve for the distance covered with respect to the ground in unit time and for the drift or correction angle (AOC). (See next paragraph.) The angle between the course to be steered (OC) and the geographic meridian (SN) is now known; consequently the compass course can be corrected to counteract the drift due to wind. The sides of the velocity triangle thus drawn are proportional to the air speed, wind speed, and ground speed.

It will be advantageous to carry the discussion of drift a little further at this point and to give arbitrary definitions, for the sake of clearness, to the names "drift angle" and "correction angle," both of which will be involved in the following description of drift indicators.

In figure 2(*b*) let (OA′) be the course the pilot wishes to make good and let (O) be his starting point. Also let (OA) represent his air speed and (AC) the wind speed in both direction and amount. The triangle (OAC) can now be drawn, since both (OA) and (AC) are completely known. The ground speed (OC) and the angle (α), which is the angular amount by which the aircraft is deviated from its desired course and which we shall call the "drift angle," are now known. This triangle is often solved in various ways by the navigator while in the air in order to determine the wind or his ground speed. But the pilot desires actually to follow the course (OA′) and to do this he must steer the compass course (OE). For this purpose it is not sufficient for him simply to apply the drift angle (α) to the direction of the course to be made good, but a new triangle must be solved. In other words, he must determine angle (β), which is the true correction to be applied to his compass course in order to overcome the component of motion due to the wind. (β) will be called the "correction angle" and can be found in terms of the angles (α) and (γ), where (γ) is the angle between the desired track and the direction of the wind.

Applying the law of sines to each triangle and remembering that the ratio of the air speed to the wind speed is the same in each, we have

$$\sin \beta = \frac{\sin \alpha \sin \gamma}{\sin (\gamma - \alpha)}.$$

The "drift angle" will thus be defined as the angle by which the craft is deviated from its compass course by the wind, while the name "correction angle" will be applied to a particular drift angle, namely, the drift angle which exists when the craft is following the desired track.

DRIFT INDICATORS.

Drift indicators are a class of instruments whose use is dependent on a view of the ground or the ocean. The usual type is based on the fact that it is possible to tell when points on the ground, floating objects on the surface of water, or patches of foam move parallel to a line which can be rotated in a horizontal plane in the aircraft.

Webster drift sight.—Probably the simplest drift sight in use is that devised by D. L. Webster. Fixed wires radiate at 10 degree intervals from a point so placed that the pilot can sight along them at the ground. By watching the points on the ground as they move by these wires, the pilot can estimate the drift angle to about 2°. A movable sighting wire which can be operated from the cockpit is sometimes used to replace the fixed wires.

Sperry synchronized drift set.—This device (fig. 3) is a combination compass and drift indicator so connected that the observer can move the lubber line on the pilot's compass and thus correct the compass course for drift without having direct communication with the pilot.

The drift indicator consists of a prismatic telescope having a series of parallel lines in the focal plane of the eyepiece. These lines can be turned by a tiller wheel until they are parallel to the apparent motion of objects on the ground. A pointer indicates on a fixed scale the angle which these lines make with the axis of the ship; i. e., the drift angle.

A wire cord is wrapped around the tiller wheel so that as the observer sets the drift lines in the telescope he moves this cord, which is attached to another tiller wheel on the compass. This second tiller wheel turns the movable lubber line, and so the pilot, who merely keeps the ship headed along the indicated compass course, automatically corrects for the drift.

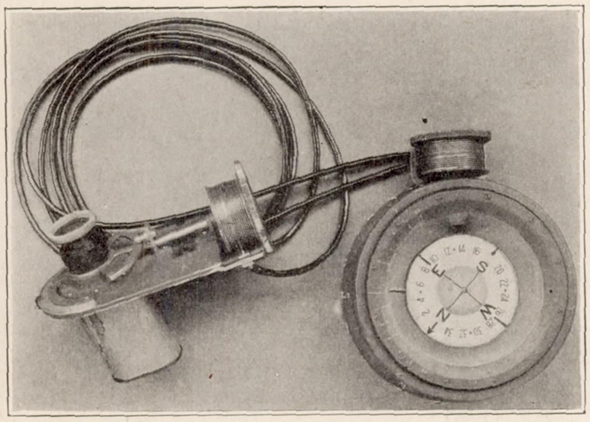

Fig. 3.—Sperry synchronized drift set.

The correction thus made is not exact, since the drift angle, as distinguished from the correction angle, is laid off. Practically the two angles are nearly equal and successive corrections for drift counteract the slight error involved.

Angus compass course indicator.—This instrument (fig. 4), designed by Capt. Angus, R. A. F., is intended to solve the velocity triangle when the air speed, the compass course, and the amount and direction of the wind are known.

A square of transparent celluloid (S) rests on the map, its center at the point of departure. An arrow at the midpoint of one of the sides marks the geographic north. The square is oriented by means of a parallel rule (R), which can be set to coincide with a convenient meridian. At the center of the square of celluloid is a circular celluloid protractor (P), which can be revolved. The points of the compass are engraved on this card. Three graduated arms (T), (A), and (W), which can be suitably adjusted relative to each other, serve to solve the velocity triangle mechanically.

The first of these, a long radial arm (T), called the track scale, is pivoted at the center of the protractor. One edge of this arm, if prolonged, would pass through the pivot (O) and is graduated in miles per hour with the zero point at (O).

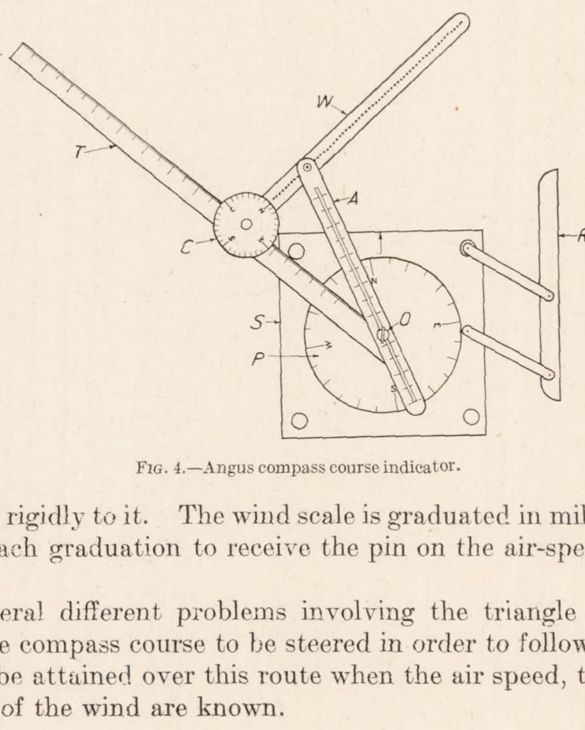

Fig. 4.—Angus compass course indicator.

Pivoted also at (O) is another arm (A). This has a longitudinal slot, so that it can be slipped by the pivot (O) and clamped there by means of a thumb screw. One end of the arm carries a pin which can be set into the holes in the third arm (W), which will be described shortly. The arm (A) is used to represent the air speed and is graduated in miles per hour with the zero at the pin.

The third arm (W) is called the wind scale. It slides on the track scale, while its direction with respect to the latter can be set by means of a small compass disk (C) attached rigidly to it. The wind scale is graduated in miles per hour and has small holes drilled in it at each graduation to receive the pin on the air-speed scale.

Although this apparatus will solve several different problems involving the triangle of velocities, its principal use is to determine the compass course to be steered in order to follow a fixed route and the ground speed which will be attained over this route when the air speed, the desired track, and the amount and direction of the wind are known.

The instrument is placed on the map with the center (O) over the point of departure and is then oriented by means of the parallel rule. The protractor is turned until the declination is laid off (i. e., a magnetic needle suspended at (O) would read zero). The track scale is laid along the course to be followed and the wind scale is set to the proper direction by means of the compass card (C), the arm being turned until the graduation on the card corresponding to the known wind direction is parallel to any convenient meridian line. The pin at the end of the air-speed scale is now placed in the hole on the wind scale corresponding to the wind speed. The air-speed scale is slid past (O) until the graduation at (O) represents the air speed. As this is done, the wind scale slides on the track scale and when the air speed is properly set, the ground speed can be read on the track scale. The course to be steered to overcome the drift due to the wind is given by the reading of the air-speed scale on the protractor.

The angle between the track and the air-speed scales corresponds to the correction angle of figure 2(*a*).

Drift or aero-bearing plate.—This instrument may consist merely of a rotating graduated circle with diametral wires for measuring the drift or it may combine with this a ground-speed attachment. (See fig. 5.) Only the latter type will be described as it includes the former.

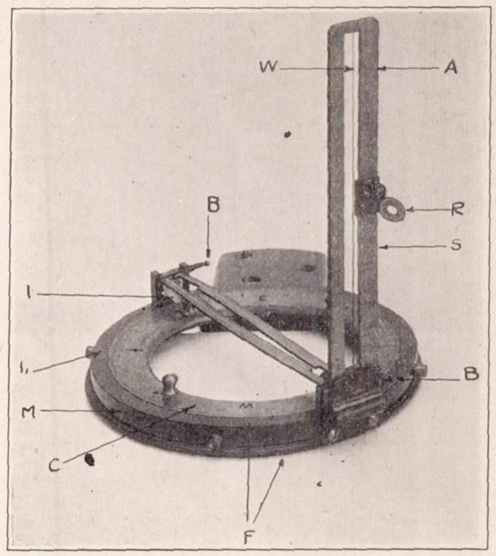

FIG. 5.—Drift bearing plate.

The frame of the instrument is attached rigidly to the fuselage with the line through the index (I_1) and the center of the fixed circle parallel to the longitudinal axis of the plane. An inner circle (C), graduated clockwise from 0° to 360° and with the cardinal points of the compass engraved on it, slides in the fixed frame (F) and can be set in any desired position. An outer movable circle (M) carries two diametral parallel lines engraved on strips of celluloid (L) together with an index (I) reading on the inner graduated circle. In measuring the drift angle, the inner circle is set with its zero at the index (I_1) of the fixed circle; i. e., in the direction in which the plane is heading. The outer circle is now rotated until points on the ground move parallel to the diametral lines (L). The index (I) on the outer circle now reads the drift angle.

The standards at the ends of the celluloid strips carry two ball sights (B) in a horizontal plane. One of the standards also carries a vertical folding arm (A) with a central vertical wire (W), and a sliding ring sight (R) whose center is in the same vertical plane as the two ball sights and is directly over one of them. This ring sight carries an index which reads on an altitude scale (S) graduated from 0 to 6,000 meters on the vertical arm. By setting the index of the ring sight to read the altitude of the aircraft, setting the outer circle so that the plane of the sights is in the direction of motion over the ground, and timing the passage of an object between the two ball sights, the ground speed can be computed from the known length of base line on the ground. (See Report No. 127 of this series.) In the case of the particular instrument just described, this base line is 5 miles or 8 kilometers.

Wind-gauge bearing plate.[6]—This is an ingenious instrument devised by Maj. H. E. Wimperis, R. A. F., to measure the drift angle by means of tail bearings and to determine the ground speed and the direction and amount of the wind by using the principle of the "wind star."

Suppose the navigator has a horizontal graduated bearing plate with a transparent glass or celluloid center. (See fig. 6.) A straightedge (AC) is pivoted at (A), (AB) being the center line of the device fixed parallel to the longitudinal axis of the airplane. The straightedge (AC)

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[6] "Air Navigation," by H. E. Wimperis. Constable & Co., Limited, London.

can be adjusted until it is parallel to the direction of motion over the ground. A line is now drawn along this straightedge on the transparent center of the plate which should be oriented with the aid of the compass. Now, suppose that (AO) represents the air speed, which is known. Then in the velocity triangle (*c*), which is properly oriented to illustrate (*a*), the line just drawn includes the side representing the ground speed (AP). The position of the point (P) on this line (AC) is not known, however, as the ground speed has not yet been determined.

Now, suppose the airplane is deviated from its course by, say, 30° or 40°. Reorient the bearing plate. Now, set the straightedge parallel to the drift lines again and draw a new line (A′C′) (fig. 6b). (A′C′) will intersect (AC) at (P), thus determining the second side of the velocity triangle representing the ground speed. The closing side (OP) represents the wind. (P) is called the "wind point" and the diagram is called a "wind star."

In designing an instrument to use the method just described, it is necessary to make some provision for varying the distance (AO) for different air speeds. Wimperis provided for this by making the pivot (A) movable along the line (AB), its motion being controlled by a thumbscrew and the proper length being determined by an air-speed scale. The drift angle can be read by an index sliding over a scale at the end of this arm. The center of the bearing plate is of glass and has concentric circles representing wind speeds differing by 10-mile intervals. The pivoted straightedge or drift bar carries speed and time scales and has a beveled edge for drawing lines on the glass plate with a glass-marking pencil. A diametral wind arrow carrying a sliding red wind point can be rotated in the fixed circle of the bearing plate. The bearing plate is graduated and has an index which enables the observer to orient it as above described.

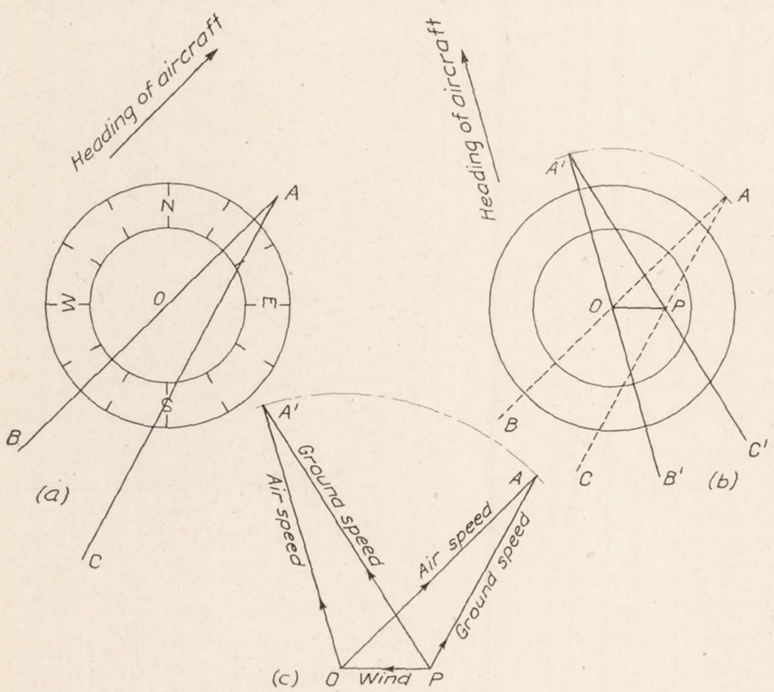

FIG. 6.—Wind star diagram.

A ground-speed attachment is also combined with this bearing plate. It consists of a vertical arm as described for the aero bearing plate and two horizontal wires, each carrying two head sights. One of these wires gives a base line on the ground of one-half mile, while the other is arranged to give the number of minutes taken to fly 30 miles.

Course-setting sight.—Another instrument invented by Wimperis is the course-setting sight designed for use in the nose of the aircraft to set off the course to be followed. Here are combined a vector triangle linkage and a bearing plate, the latter commonly, although not necessarily, containing a compass needle. Briefly, the action of this instrument is as follows: The air speed is set off on the air-speed bar. The machine is then flown directly up the wind, this being done by adjusting the course until the sight shows no drift. The bearing plate is oriented by means of the compass needle. The aircraft is then turned off this course by about 90°. The bearing plate is reoriented by the needle and the wind scale adjusted until points on the ground appear to travel along the drift wires. The ground speed and wind speed can now be read.

The geometry of the solution is as follows (see fig. 2*a*): By flying up the wind we determine the direction (CA) of the wind vector. For any course we know the direction and amount of the air-speed vector (OC). Now, if we observe the drift, we know the direction (OA) of of the ground-speed vector, and the intersection of a line through (C) in the direction of the wind vector and a line through (O) in the direction of the ground-speed vector gives the point (A), and the wind and ground speed are then completely determined.

Christmas drift indicator.—This instrument (fig. 7), invented by Pilot Valdemar de Christmas, of the French Air Service, fits over the map board used in the French airplanes and has an adjustment at right angles to the motion of the map. With the aid of this instrument, the pilot can take the air without knowing the wind and by a single observation can obtain the correction angle, thus enabling him to steer so as to follow the desired track.

The apparatus is composed essentially of two circular limbs, an inner one (A) rotating inside of the other (B), which is fixed. The outer one is graduated from 0° to 360° clockwise in the usual manner. The interior limb carries a transparent sheet of mica laid off in kilometer squares to the scale of the map. A wedge-shaped pointer (P), sliding on the circumference of the outer circle, reaches to the center and is also graduated in kilometers from the center outward.

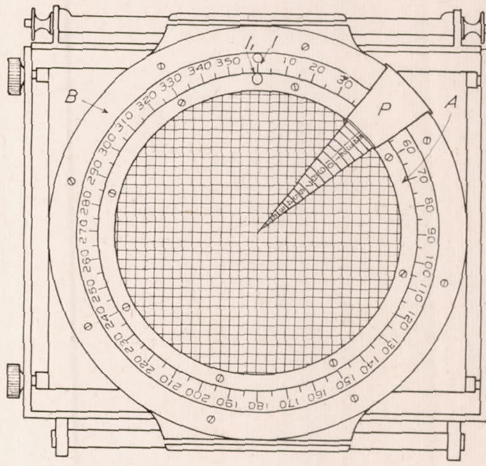

FIG. 7.—Christmas drift indicator.

Before leaving the airdrome the navigator marks on the map the route to be followed and the geographic meridian is drawn through the starting point. The drift indicator is mounted on the map case and is adjusted, together with the map, until its center is over the starting point. The zero graduation (I) of the outer limb is set to the meridian on the map and the index of the interior limb (I_1) is now set on the desired track, thus indicating on the outer limb the track angle. Making the necessary correction for declination, the pilot lays off the track angle on his compass by means of a movable index and flies so that the compass needle is directed toward the index.

At the end of a suitable period—three minutes, for example—he notes the point directly beneath him on the ground and marks it on the map. This new point (O′) is now taken as a center for the drift indicator and the slide is turned until the graduation corresponding to the air distance covered during the three-minute interval cuts the route line on the map in point (B). (See fig. 2*c*.) Angle (α) is here the drift angle and angle (β) the correction angle. Now, if the ship is headed at an angle (β) to the route to be made good and to the windward of the latter, it will move over the ground, following a route parallel to the route to be made good at a ground speed represented by (O′C). Consequently the duration of the trip can be computed.

Since the center of the drift indicator is at the point (O′) to which the ship has drifted at the end of the three-minute interval, by turning the slide until it cuts the point (A), where the ship would have been at the end of three minutes had there been no wind, the pilot can read from the slide the distance which the wind has traveled in three minutes and then from the graduated circle the angle ($180° + \gamma$). Or by first moving the drift indicator until its center is at A, he can read the angle (γ) and the wind speed directly. The ground speed represented by (O′C) can be determined by measuring the equal distance (AB) with the aid of the graduated inner limb.

Crocco drift and ground-speed indicator.—This instrument (see fig. 8), designed by Col. Crocco, of the Italian Air Service, has been used in a modified form by the United States Naval Air Service and is being adopted in this form for dirigibles by the United States Army Air Service.

It performs two distinct operations: It measures the ground speed and the angle of drift, and it solves the velocity triangle. The instrument is set in the tail with the long side of the frame parallel to the longitudinal axis of the ship. The arm (A) at the extreme right of the photograph can be turned by means of the large knurled screw (S) until objects on the ground appear to move along the longitudinal wire (W), when the angle between the objects and the axis of the plane—i. e., the drift angle—can be read on the graduated drift sector (C) at the base of the upright (U) by means of the index (I) shown on the right. If it is desired to pick up a particular object on the ground, the arm (A) can be moved without altering its angle with respect to the axis of the airplane by the parallel motion (P) connecting the arm to the base. An adjustable eyepiece (E) on the upright serves to keep the eye in the proper position and to hold it steady.

The ground speed can be determined by measuring with a stop watch the time it takes an object astern on the ground to travel from the fixed wire (F) to the movable wire (M) when the eye is at the eyepiece (E). The movable wire (M) is set to correspond to the altitude by means of the scale on the ground-speed arm (A). Two scales are engraved, one on either side of the arm, the first giving altitudes from 600 to 3,000 meters and the other from 3,050 to 6,000 meters. To these scales correspond base lines on the ground of 600 and 1,200 meters, respectively, so that when the movable wire is properly set for altitude, the distance actually traveled, when a point on the ground moves from one wire to the other, can be computed.

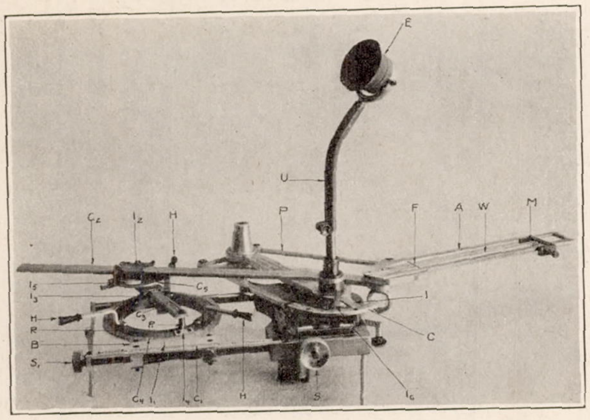

FIG. 8.—Crocco drift indicator.

It has already been explained how the ground speed and the drift angle are determined. The air speed, also, is known from the reading of the air-speed indicator corrected, if necessary, for air density. Once these three quantities are known, the velocity triangle can be solved for the direction and amount of the wind by means of the instrument.

The air speed is first set on the scale (C_1) by moving the sliding base (B) parallel to the longitudinal axis of the aircraft by means of the thumbscrew (S_1) until the index (I_1) reads the air speed.

The ground speed is now laid off on the ground-speed or track scale (C_2) by sliding the index (I_2) to the proper reading. The track arm (C_2) carries three scales, the two outer ones corresponding to the two altitude scales on the ground-speed arm (A) and graduated in seconds, so that the time taken for an object to pass between the wires (F) and (M) can be laid off directly without the necessity of computing the ground speed. The central scale on (C_2) is in meters per second, and gives the ground speed corresponding to the measured number of seconds.

The graduated arm (C_3) represents the wind in direction and amount. This arm is mounted on two posts (P_1) (only one of which is visible in the figure) attached to the ring (R), which can be rotated relative to the graduated circle (C_4), a part of the base (B). (C_3) can slide past the track arm (C_2) and can change its direction relative to the latter. Holding the index (I_2) against the ground speed on the track arm, the navigator turns the wind arm (C_3) by means of the handles (H) and the rotating ring (R) until the index (I_6), which is rigidly attached to the arm (C_2) and which reads zero when the track arm is parallel to the longitudinal axis of the ship, coincides with the index (I). As (I) is set for the drift, this procedure amounts to setting the arm (C_2) for the drift.

The procedure outlined above has brought the wind arm into such a position that the amount and direction of the wind can be read directly. The index (I_3) indicates on scale (C_3) the speed of the wind. The direction of the wind with respect to the longitudinal axis of the plane can be read on scale (C_4) by means of index (I_4). The semicircular double scale (C_5) and the index (I_5) give the angle between the track and the wind.

The process above described solves completely the velocity triangle. Now, if the navigator wishes to determine the correction angle which will enable him to follow a chosen track over the ground, he can reverse this process. He first sets off his air speed on scale (C_1). He then sets on scale (C_3) the wind speed just found, and turns the scale by means of the handles (H) until index (I_5) reads the known angle between his desired track and the wind. The correction angle can then be read on the drift sector (C) by means of index (I_6).

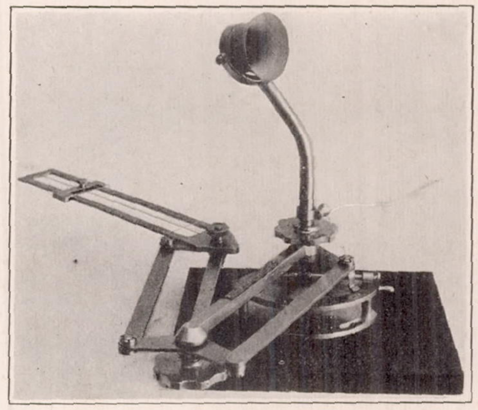

Fig. 9.—Pioneer drift indicator.

The Crocco drift indicator is essentially an instrument for dirigibles, where the matter of size and weight are not so important as in heavier-than-air craft. However, by the substitution of a computer for the portion of the instrument which solves the velocity triangle we can make the indicator much lighter and more compact. Drift indicators modeled after the Crocco, but altered as just suggested, were used successfully in the flight of the United States Navy *NC* boats across the Atlantic.

Pioneer drift indicator.—A still later modification of the Crocco drift indicator is to be found in the Pioneer drift and ground-speed indicator (fig. 9). This instrument measures the ground speed in a manner similar to that described above. The arm has two altitude scales, having corresponding base lines on the ground of one-tenth and four-tenths nautical miles.

Le Prieur navigraph.—This instrument (fig. 10) is a synchronized drift set. It is comprised of two parts: A derivograph, with which the navigator plots a drift line, and so determines the drift angle and the wind vector, and a repeating disk placed in front of the pilot connected to the derivograph by means of a flexible cord, so that its indications are synchronous with the latter, thus enabling the navigator to indicate to the pilot the proper course to follow.

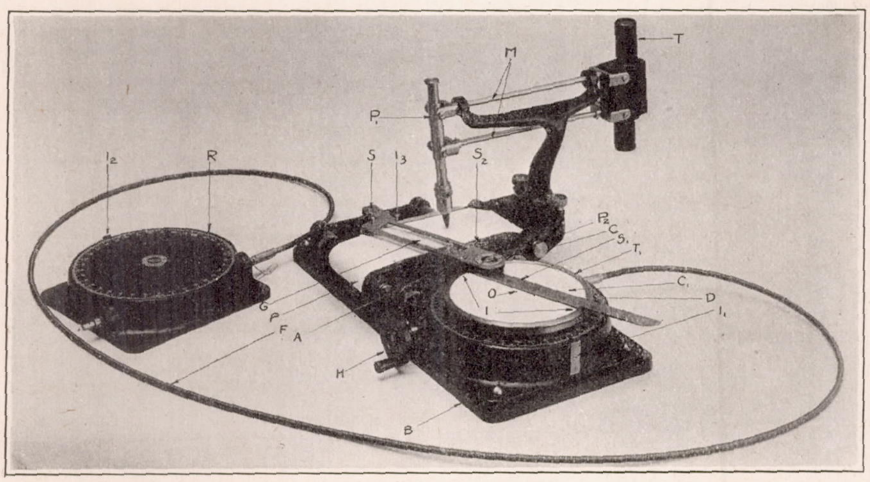

Fig. 10.—Le Prieur navigraph.

A feature of the navigraph which is not found in the other drift-measuring instruments described in this paper is the means provided for determining the drift more accurately than can be done by sighting along a wire and estimating the direction of motion over the ground. Owing to the yawing, rolling, and pitching of the aircraft, points on the ground appear to follow a sinuous line whose general direction is often hard to estimate.

With the navigraph an object upon the ground is followed with a telescope (T) (fig. 10) and a series of points is plotted on the sheet of paper (P) with the pencil (P_1), which is connected to the telescope (T) by means of the parallel motion (M). In this way a drift line is obtained on (S) for the object on the ground whose relative motion is being followed. The advantage of this drift line lies in the fact that it enables the navigator to obtain the mean drift by averaging the irregularities due to the unavoidable pitching and yawing of the aircraft. In practice several drift lines may be obtained from as many objects on the ground and the mean of these lines taken. The sheet of paper (P) is mounted on rollers and so can be set to any desired position.

The operation of the derivograph is based upon the "wind star" principle as is the Wimperis wind-gage bearing plate. By measuring the drift angle for two different courses the navigator can determine the wind vector and the correction angle which should be applied to the bearing of the desired track to give the proper compass course.

To make the following discussion of the principle and operation of the navigraph more concrete, the following problem will be assumed:

The navigator wishes to follow a track whose direction is 40° (N. 40° E.). His air speed is 100 M. P. H. How can he determine the compass course to be followed?

The derivograph is fixed with the long side of its base (B) parallel to the longitudinal axis of the aircraft. On the base are mounted (1) a movable carriage (C) supporting the roll of paper and the telescope, pencil, and parallel motion already described, and (2) a graduated disk (D), which can be rotated about a vertical axis by means of the handle (H). This disk is graduated in degrees clockwise from 0° to 360° and the cardinal points of the compass are engraved upon it: north corresponding to 0°, east to 90°, south to 180°, and west to 270°. A circular table (T_1) surmounts the disk (D) and can be moved relative to (D) against friction. (T_1) carries two indices (I) 180° apart, and a fixed index (I_1) is mounted on the longitudinal center line of the base (B) so as to read on the graduated scale on (D).

A circular chart (C), on which are drawn a series of concentric circles and parallel lines, is fastened to (T_1) with its diametral line coinciding with the indices (I). (T_1) is then turned by friction relative to the disk (D) until one index (I) reads the bearing of the desired track; in this case, 40°. The table (T_1) is kept in this position relative to (D) throughout the flight. It will be observed that, if the aircraft is headed along the course indicated on (D) by the index (I_1), (D) is properly oriented and the indices (I) and the parallel lines on (C_1) lie in the direction of the desired track. This relation is maintained during the flight with the aid of the repeater disk (R) as follows:

The graduated disk (D) is connected to the repeater disk (R), which is graduated exactly like (D), by means of a flexible cord (F). (R) is so set that the index (I_2) reads the bearing indicated by (I), corrected for magnetic declination. The pilot watches the repeater (R) and steers his ship so that his compass reads the bearing shown by the repeater.

At the start of the flight the disk (D) is turned until the bearing of the desired track (40°) is opposite the index (I_1). The pilot, following the instructions given by the repeater, heads the ship parallel to the desired track. The navigator plots a drift line on the paper (P) for an object on the ground. He then sets the movable carriage (C) so that the index (I_3) (not visible in fig. 10) reads the air speed on the scale (S). When this is done the center (O) of the chart (C_1) is opposite the graduation giving the air speed on scale (S_1) on the arm (A), which is pivoted at (P_2). The arm (A) can be turned about (P_2) so that the line ruled parallel to the fiducial edge of (A) on the glass (G) coincides with the drift line just plotted. The drift angle can then be read on the scale (S_2).

When the arm is set for zero drift angle and so passes through the center (O) of the chart (C_1), it represents the air-speed vector of the velocity triangle. The pivot (P_2) corresponds to the air-speed-ground-speed vertex of the velocity triangle. When the arm is set to the proper drift angle, it then represents the ground-speed vector in direction, but the length of this vector is not known unless either the ground-speed or the wind vector is known.

The principle of the navigraph is shown in figure 11. The inner circle (BDGH) represents the chart (C_1). The outer circle (NESW) represents the graduated compass disk (D). The outer arc (AFC) represents the locus of positions of the pivot (P_2). In the actual instrument the compass disk and chart rotate while the pivot remains fixed, but in figure 11, for simplicity, the disk and chart are considered as fixed and the pivot is considered to move in the arc (AFC). This is justifiable since the relative motion is the same.

When the navigator has set the arm (A) according to the drift line on (P) he draws along the fiducial edge of the arm (A) the line (GB), which is known to include the point (E). The intersection of the wind and ground-speed vectors is not yet known. To determine the position of (E) on the line (GB), the navigator first arbitrarily selects a new course (in this case 320° or N. 40° W.) and rotates the compass disk by means of the handle (H) until the index (I_1) reads 320°. This corresponds in figure 11 to rotating the pivot (P_2) from (A) to (C). The navigator now determines a new drift line on (P), sets the arm (A) to this drift line, and draws the line (HD) (fig. 11). The intersection of (GB) and (HD) determines the wind point (E) and the line from (O) to (E) represents the wind vector.

Now that the wind vector is known, the navigator can correct his compass course so as actually to follow the desired track. If he rotates the compass disk (D), holding the arm (A) in contact with the wind point (E) until the arm is parallel to the lines on the chart, the reading of the index (I_1) will be the course which should be followed. This is shown in figure 11. The rotation of the compass disk is represented by the shifting of point (C) to (F), where (FE) is parallel to the system of lines on the chart. These lines point always in the direction of the desired track, and therefore, when the arm (A) is adjusted as explained, it is parallel to the desired track. But since (A) also passes through the point (E), it includes the ground-speed vector for the desired track and so should coincide with the direction of motion of points over the ground. This can be checked by observing the motion of suitable points. Usually a small discrepancy will be observed owing to instrumental errors, observational errors, and changes in the wind. In this case a second trial will usually suffice to give the proper course with sufficient accuracy.

When the arm (A) passes through the wind point (E), the graduation on the arm opposite this point gives the ground speed.

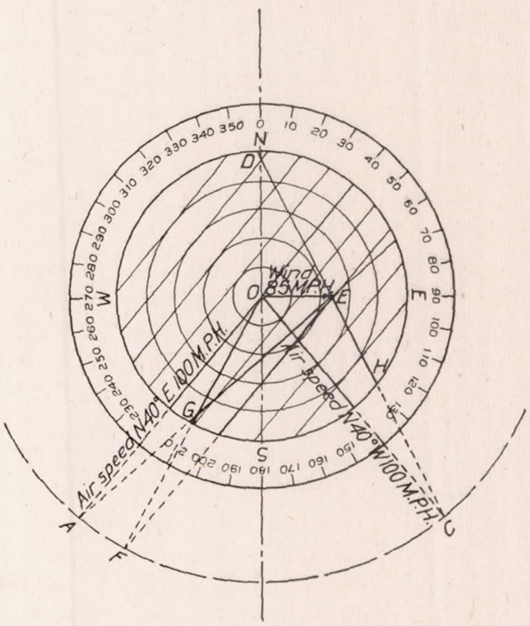

FIG. 11.—Principle of navigraph.

COMPUTERS AND PLOTTING DEVICES.

Campbell-Harrison course and distance calculator.—This computer (fig. 12, A and B) is a simplified modification of the naval Battenberg course and distance indicator. It consists of a circular disk rotating inside a ring which is graduated from 0° to 360° clockwise. The disk is laid off in squares of suitable size, reading from 0 to 140 by intervals of 10 units from the center of the circumference. Two rotating arms graduated from 0 to 140 to the same scale as the disk and carrying slides complete the device.

In the form just described, the computer can be used for solving the velocity triangle and can be used in an approximate way as a slide rule for computing times and speeds.

Appleyard course and distance calculator.—This computer is similar to the one just described except that it includes also a computing dial or circular slide rule on the circumference. (See fig. 12C.)

The computers shown in figures 12 A and B have central disks about 7 inches in diameter, while that of the Appleyard computer is considerably smaller. The tendency in this country is to increase the size of the disk and the number of graduations in order to make a more accurate instrument.

The use of these computers is illustrated by the following examples:

(1) (fig. 12A). The course steered is 104° and the air speed is 110 miles per hour. The wind is blowing from 205° at the rate of 40 miles per hour. What is the direction of the track and what is the ground speed?

It may be said, in general, that the arms should be used for the known quantities and the disk for the unknown. This rule is applicable to nearly all cases. Proceeding in this way, we set one arm to 205° and move slide to 40. Set the other arm to 104° and set slide to 110. Rotate the disk until the arrow is parallel to the line through the indices of the two slides, the sense of direction being obtained from the air-speed arm. The direction of the track is then read opposite the arrow as 85° and the ground speed is given by the distance between the two slides as 20 + 105 = 125 miles per hour. The two arms and the line through the indices of the slides form the velocity triangle, which is solved with the aid of the graduations on the computer.

(2) Given the course steered as 120°, air speed 90 miles per hour, observed track 95°, ground speed 100 miles per hour. What is the amount and direction of the wind? (See fig. 12C.) Lay off on one arm the ground speed 100 miles per hour and turn the arm until it reads 95°, the observed track. Lay off on the other arm, 90 miles per hour, the air speed, and turn this arm until it reads 120°, the compass course. Turn disk until the lines are parallel to the line of the indices. The arrow then reads 31°. The sense of direction is given by the relative directions of the course steered and the observed track. In this case the wind is blowing

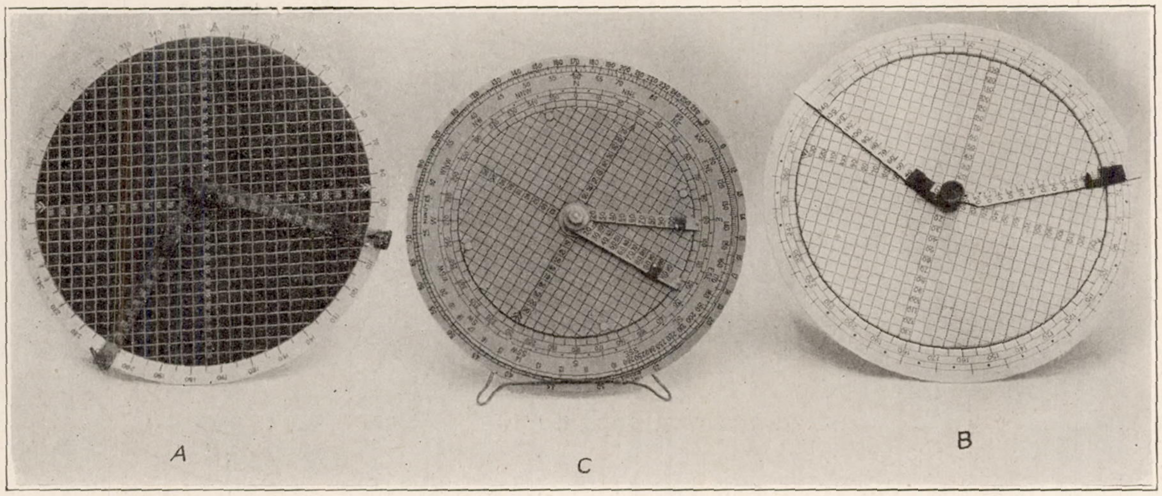

FIG. 12.—Course and distance calculators.

toward 31° or from 211°. The speed of the wind is found from the distance between the two indices, in this case about 42 miles per hour.

(3) Given the same data as in (1), how long will it take to fly 480 miles? The proportion used is

$$\frac{\text{time required in minutes}}{60}=\frac{\text{distance covered in miles}}{\text{ground speed in miles per hour}}$$

or in this case

$$\frac{\text{time}}{60}=\frac{480}{125}$$

(Fig. 12B.) Set slide on one arm to 125 and turn arm until the index lies on the line through 60. The other arm is not used. Read line on disk corresponding to 480 on arm. In this case we obtain 230 minutes or 3 hours 50 minutes.

The Bigsworth protractor, parallels, and chart board.—This is one of the most convenient available outfits (fig. 13) for plotting and determining courses, finding position, etc. Two sizes are provided, 14 and 17 inches square, depending on the room available. A number of charts can be carried under the celluloid upper surface of the board and held in place by clips with the one desired for use placed uppermost.

A parallel motion carrying a celluloid protractor and straightedge can be clamped to the side of the board in any desired position. The parallels are fitted with a hinge, so that the protractor can be lifted off the board if so desired.

The protractor can be set with its arrow pointing magnetic north by means of the compass rose or by a convenient meridian and the known variation for the region.

For measuring distances, two interchangeable protractors are provided, one graduated in inches and tenths for the standard charts which are drawn to the scales 10 nautical miles to the inch for General Charts and 3 nautical miles to the inch for Coastal Charts (these specifica-

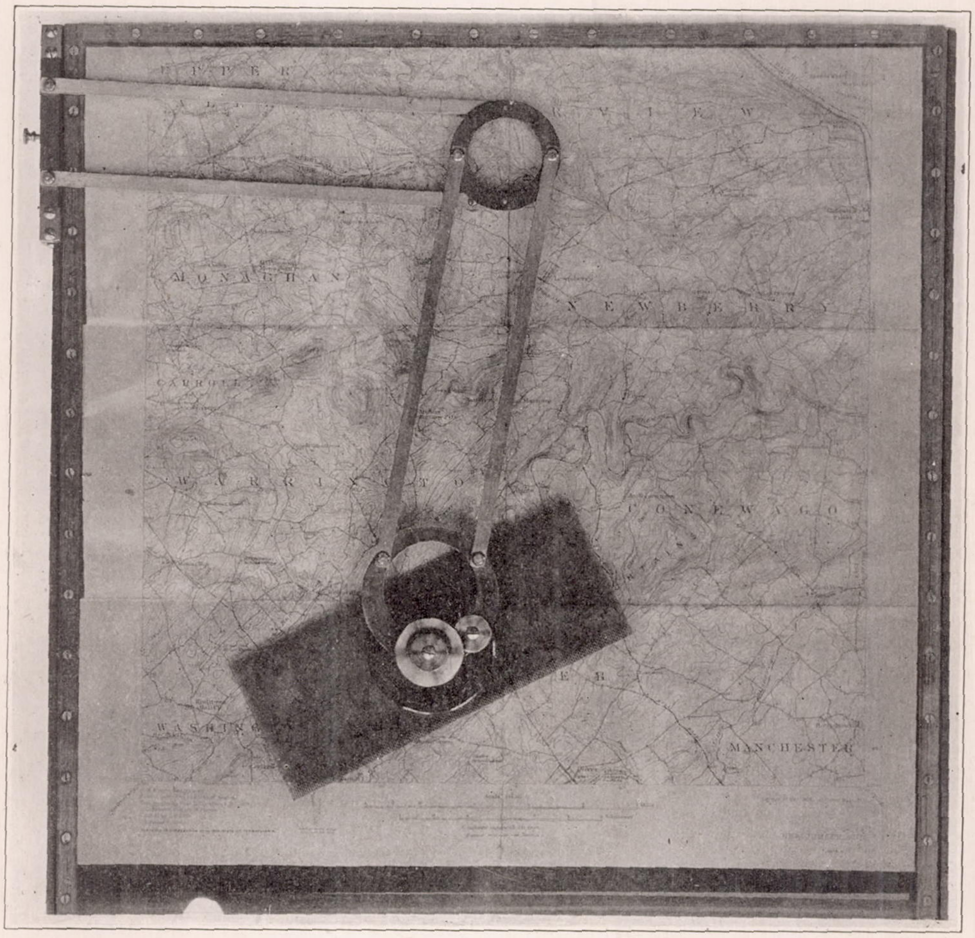

FIG. 13.—Bigsworth chart board.

tions are for the British Air Service), and the other graduated in miles and halves on a scale of $\frac{1}{200000}$.

A special pencil is used for drawing on the celluloid surface, the marks being easily erased by rubbing with the finger.

Map cases.—A number of map cases have been devised, most of which are quite similar in form. They consist of small rectangular cases with the map, which is cut in a long narrow strip, including the route to be covered, mounted on two rollers which can be revolved by hand, thus bringing the desired portion of the map into view. A celluloid cover protects the visible surface of the map. A light is sometimes provided beneath the portion of the map which is in use to illuminate the latter for work at night.

Protractors.—Various protractors have been devised for aerial use. These consist usually of a circular or square piece of celluloid with angles laid off on the circumference or the sides and often with squares ruled on them to the scale of map used. A string or movable arm is used to determine courses.

ASTRONOMICAL OBSERVATION.

GENERAL PRINCIPLES.

Astronomical observations are made for the purpose of checking or correcting the position as found by dead reckoning. The observations involve the measurement of either the altitude or azimuth, or both, of the sun or some other heavenly body. In the majority of cases the altitude alone is measured, since this leads to the customary simple "Sumner line" method, which has been used for about 80 years in marine navigation.

It was natural that in the first attempts at aerial navigation by astronomical observation the methods and instruments which long experience had shown to be the best for marine navigation should be adopted. The aviator, however, is concerned with somewhat different requirements and conditions from those affecting the mariner. He has greater need of an artificial horizon for use with his sextant. Owing to the much higher speed of his craft, he must be able to reduce his observations quickly. Fortunately, a slight sacrifice of accuracy is permissible in accomplishing this, since there are no dangerous rocks and shoals to endanger the aircraft, and an error in position which might increase the duration of the voyage for a mariner by an hour would mean but a few minutes additional for the aviator. Only in exceptional cases is it necessary for the aviator to know his position with great accuracy, aside from landing in a fog.

The above considerations have already brought about for aerial use the modification of the marine sextant, new methods of reducing observations, and the use of special maps to facilitate the graphical work involved in plotting position. The nature of the observations made still remains practically the same as in marine navigation, but the urgent need of simplifying the work has led to the attempt to obtain latitude and longitude more directly than is possible with the orthodox methods.

Sumner line method.—In using the "Sumner line" method, the observer measures the altitude of some celestial body, say the sun. He then knows that he is on a small circle whose radius in nautical miles is equal to the zenith distance of the sun in minutes of arc and whose center is the subsolar point. The position of the subsolar point can be computed from the Greenwich solar time, the equation of time, and the declination of the sun. The first of these quantities is read from a chronometer and the second and third are obtained from tables in the Nautical Almanac. If observing a star, the observer makes use of the right ascension of the star as determined from the Nautical Almanac.

In practice he usually knows his location within 2°, so only a small portion of the curve is needed. This small portion is assumed to be a straight line tangent to the circle and is called a "Sumner line."

St. Hilaire method.—A modification of the above procedure is found in the Marcq St. Hilaire method. The observer lays down on the chart his dead reckoning (D. R.) position. If actually at this point, he would at a definite instant see the sun at a particular altitude and azimuth, both of which can be computed. The observer performs these computations and measures the true altitude of the sun. His computed altitude will usually differ from his observed altitude by a few minutes of arc, depending on the accuracy of the D. R. position assumed. A line is drawn through the D. R. position in the computed direction of the sun from the observer. The Sumner line is now drawn at right angles to this line and at a distance from the D. R. position of as many nautical miles as there are minutes of arc difference between the observed and computed altitudes. If the observed altitude is greater than the computed, the Sumner line is nearer the sun than the D. R. position; if less, the reverse is true. The most probable position is at the intersection of the Sumner line and the D. R. azimuth line, since the D. R. position was the most probable location of the ship before the altitude of the sun was measured, but all that is positively known is that the craft is at some point on the Sumner line. If the observer has both the sun and moon available, or if two suitable stars are visible, he can measure the altitudes of the two bodies, thus obtaining two Sumner lines whose intersection will fix his position. Or if he can measure the azimuth of the sun, as well as its altitude, his position is determined upon the Sumner line.

Direct measurement of sidereal time.—A radically different and theoretically much simpler method of determining position has been suggested for aerial use. In this method the observer measures the altitude of Polaris and the angle through which the vernal equinox has turned since upper transit at the observer's present meridian. The corrected altitude of Polaris gives directly the latitude of the observer. The rotation of the vernal equinox is determined from β Cassiopeiæ, which has approximately zero right ascension. Measuring this angle in the equatorial plane, the observer obtains local sidereal time. Then if he has a chronometer giving Greenwich sidereal time, he can find his longitude by taking the difference of these two times.

SEXTANTS.

DIFFICULTIES OF USE IN AIRCRAFT.

The sextant, as might be expected, is at present the universal instrument for astronomical observation from aircraft as it has been for seagoing craft. The conditions under which it is used in aeronautics are often much more adverse than in marine navigation. A very appreciable difficulty is found in using it in an airplane. The force of the wind makes it difficult to hold the instrument and affects the vision, the sun or the particular piece of horizon beneath the sun may be obscured by the wings or by a strut, the observer's fingers may be numbed with the cold; and when we add to these a cramped position, it can be seen that the navigator's task is not an easy one.

NATURAL HORIZONS.

The horizon used as a basis for measuring the altitude of the celestial body may at times present serious problems both as to its visibility and as to the magnitude of the dip correction. The most favorable conditions are found when the sea horizon is visible or one formed by flat land is available. Observations can then be made with nearly the precision obtained on shipboard.

A small error is introduced, however, in the reduction of the observations owing to the uncertainty as to the correction for the dip of the horizon. Theory tells us that the dip in minutes of arc is almost exactly equal to the square root of the height in feet and this relation has been confirmed up to an altitude of about 12,000 feet.[7] The error involved in the dip correction is thus dependent upon the accuracy with which the height of the aircraft above the surface of the sea or the land can be determined. This height is obtained from the altimeter carried on board the craft. Very few altimeters which have been properly tested and accepted, unless damaged by rough handling, will show an error greater than from 200 to 300 feet at an altitude of 12,000 feet and this maximum error diminishes with decrease in altitude to about 100 to 120 feet at 1,000 feet altitude. Under these circumstances the greatest error in determining the dip correction would be about 1.5 minutes at altitudes between 1,000 and 12,000 feet. This accuracy will not be attained, however, unless the altimeter is set at the start of the flight to read the altitude corresponding to the existing atmospheric pressure at the starting point and unless the reading is occasionally checked during long flights by dropping down close to the level of the sea in order to take account of local changes in atmospheric pressure. It seems reasonable to assume that in the future we may expect to see the same degree of intelligence exercised in aerial navigation as is found in marine navigation, and in this case the correction for dip should never be in error by more than two or three minutes, an amount which, when added to the error of observation, is small compared with the errors which are involved when artificial horizons are used.

In the clearest weather the sea horizon may be visible up to an altitude of about 10,000 feet, and a horizon formed by flat land, owing to its greater contrast, has been seen up to 12,000 feet.[8] Ordinarily no such range of visibility is found on account of haze in the atmosphere. Even when the horizon is seen distinctly at sea level, it is usually found that the line between sea and sky becomes less and less clear with increasing altitude, until, at a height of from 1,000

[7] "Report on the Navigation of Aircraft by Sextant Observations," by H. N. Russell, Proceedings Astronomical Society of the Pacific, June, 1919, vol. 31, No. 181, pp. 129–149.

[8] H. N. Russell, loc. cit.

to 2,000 feet, depending on atmospheric conditions, it is indistinguishable. However, by climbing still higher, the aviator often finds that a horizon reappears distinctly at from 4,000 to 6,000 feet. The new horizon is formed by the upper surface of the haze or mist which lies over the water and which is not opaque to the observer at sea level, since the horizon seen from this height is only about 5 miles away. With increasing altitude this distance becomes rapidly greater, until at 1,000 feet the observer is sighting through over 30 miles of haze through which rays of light from the horizon may be unable to penetrate. By continuing to climb he may reach a point where the upper surface of the haze furnishes another natural horizon, but one whose altitude is not usually known.

In some cases it is possible to determine the altitude of the upper surface of the haze when climbing through it. In such a case it is possible to determine the dip correction with fair accuracy if it is known that the horizon is level. Russell in his work at Langley Field (loc. cit.) found that during the months of August and September observations made on haze horizons were almost without exception reliable, whereas in November similar observations were valueless. He concluded from his work that the layers of haze were nearly level in summer, while in the late autumn irregularities existed. In several cases his observations indicated that he had sighted on a ridge of haze instead of a true horizon.

Under such conditions the use of an artificial horizon is an absolute necessity. If the haze furnishes a level horizon we can dispense with a knowledge of its height by using a sextant like the Baker, or possibly by using a dip-measuring instrument such as has been occasionally used at sea. But if the navigator does not feel confident as to the uniformity of the horizon, he had better discard it and avail himself of an artificial horizon instead.

Clouds occasionally furnish good natural horizons, but, as in the case of haze horizons, they must be used with caution.

ARTIFICIAL HORIZONS.

In probably a majority of cases it will be found necessary to use an artificial horizon in making astronomical observations from aircraft. In this event a vertical reference line is necessary.[9] Since we must have recourse to gravity in order to establish and maintain a vertical line in an airplane, whatever device we use for the purpose, such as a level or plumb bob, will also be influenced by the accelerations to which the airplane is subjected. Of these accelerations the most important are the linear accelerations in the line of flight and the angular accelerations accompanying a change in course. Even in straightaway horizontal flight in smooth air, oscillations in pitch accompanied by changes in speed are going on continuously. Such oscillations may reach an amplitude of 1° or more with a period of approximately 20 seconds, the latter depending upon the free period of oscillation of the airplane used.

A fore-and-aft level will not indicate accurately the oscillations of the airplane in pitch, owing to the linear accelerations in the flight path which accompany the angular motion. Lucas[10] has shown experimentally with the aid of a solar reflector that a longitudinal level indicates a deflection of only about one-third of the true deflection of the airplane, and, furthermore, that its movement is one-quarter of a period out of phase with the movement of the airplane.

In a turn, a cross-level bubble tends to set itself normal to the resultant of the centrifugal force and the gravitational component, and if the bank is well executed the bubble remains at the center of the glass, even though the airplane may be inclined 50° or more. Consequently the indication at any instant of a level or short pendulum can be accepted as indicating a vertical line in an airplane only if the airplane is known to be free from accelerations.

The application of gyroscopic principles to artificial horizons has also been attempted. A gyroscope mounted in gimbals with its spin axis vertical can be given a very long period of oscillation by suitably adjusting the position of the center of gravity. A period of 100 seconds or more can readily be secured in this way, corresponding to a pendulum 5 miles long. Since

[9] The assistance rendered by Dr. L. J. Briggs in writing the portion of this report dealing with the establishment of a vertical reference line in aircraft is acknowledged.

[10] "The Oscillations of an Aeroplane in Flight," K. Lucas (British Advisory Committee for Aeronautics). Report 1915-16; 267-277.

this period is large compared with the oscillation periods of the airplane, the chances of progressively building up a large oscillation of the gyroscope from the oscillations of the airship are minimized. The spin axis of the gyroscope thus tends to hold a vertical position in straightaway flight, even though the airplane is constantly oscillating. The system containing the gyroscope is then said to be stabilized.

Careful piloting is an absolute necessity if an artificial horizon is used. If this condition is met, the errors of observation will be found to average from 10 to 20 minutes of arc, while with careless piloting the errors become so great as to make the results useless.

The development of a satisfactory artificial horizon has proceeded along two general lines: First, the attempt to build an auxiliary horizon to be used with a marine type of sextant much as the mercury horizon has been used, and second, to attach the artificial horizon to the sextant.

Pendulum artificial horizon.—A horizon of this type was designed and used by H. N. Russell (loc. cit.) in connection with his investigation of the navigation of aircraft by sextant observations. It consists of a pendulum about 10 inches long mounted in gimbals and having a speculum mirror set horizontally on top of it. The bob is arranged to swing in a pot containing a viscous liquid for damping vibrations. The whole is protected from the wind by a case.

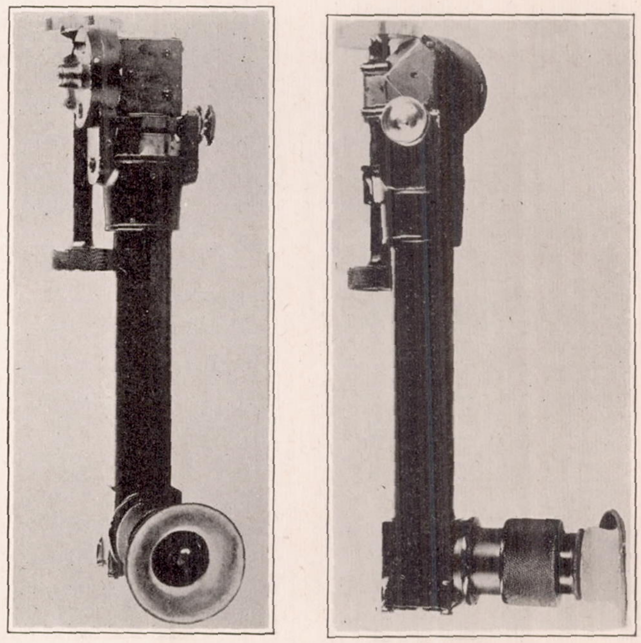

FIG. 14.—Baker sextant.

Satisfactory observations upon both the sun and the moon were secured with the aid of this instrument, while provisional tests at night indicated that it could be used for star observations.

Engine vibration caused little trouble when the instrument was mounted upon a suitable shock-absorbing substance. Probably the most serious objection to an artificial horizon of this type, whether gravitational or gyroscopic in its nature, is that it is heavy and cumbersome and has to be moved to different positions for different bodies.

SEXTANTS USING NATURAL HORIZONS.

In the following description of sextants it will be assumed that the reader is familiar with the principle and the operation of the ordinary sextant. Only the sextants which are particularly adapted to aerial work will be described.

Marine sextants.—These are of the ordinary type used in marine navigation and will not be described here. For aerial use a telescope of low power and large field should be used. The graduations on the arc should be heavy and the vernier should be easily read without the aid of a reading glass.

The Baker sextant.—This instrument (figs. 14 and 15) possesses the unique feature that it eliminates both the correction for the dip of the horizon (when the horizon is level) and for the semidiameter of the body. This not only adds to the rapidity of obtaining the altitude, but it removes the uncertainty due to the lack of knowledge as to the actual height of the aircraft above the horizon used.

The elimination of these two corrections is accomplished by reflecting into the field with the image of the sun the image of the horizon directly under the sun and that of the horizon opposite it. The observer sees the two horizons, one of which is inverted, with an open space between, the width of this space depending on the sum of the dips of the two horizons. Now, if he bisects the space between the two horizons with the image of the sun, he eliminates the dip and semidiameter corrections.

It has already been pointed out that this sextant can be used only when the horizon is level. This fact makes it useful in only a few cases when the ordinary type of sextant can not be used.

Fig. 15 illustrates the principle of the Baker sextant. The fixed horizon prisms (H) are set at the top of a vertical tube (V) high enough to reach above the observer's head as he looks into the eyepiece (E). This is done so that both back and front horizons may be visible simultaneously. These prisms reflect rays of light from the horizons down through the vertical tube (V) to the prism (P), where they are reflected horizontally to the eye at (E). An index prism (I), rotating about a horizontal axis perpendicular to the plane of the paper, is controlled by a knurled thumbscrew carrying a micrometer head, which operates the altitude scale as well. This index prism catches rays of light from the celestial body, reflects them through a small circular hole drilled vertically through the joint between the prisms (H) down parallel to the rays from the horizons until they are reflected by the prism (P) to the eye. The sextant itself is shown in figure 14.

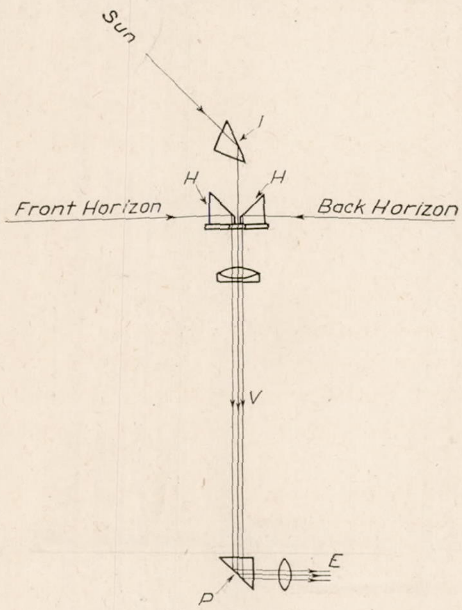

FIG. 15.—Principle of Baker sextant.

BUBBLE SEXTANTS.

The artificial horizon sextants most commonly used are of the bubble type (fig. 16). A bubble tube of the ordinary type or of the circular type is used and the image of the celestial body is brought into coincidence with that of the bubble when the bubble is at the center of the tube.

Byrd bubble sextant.—A sextant of this type (fig. 16A) used considerably in naval aviation has been developed by the United States Navy. This sextant is very similar in appearance to the ordinary marine sextant and can, in fact, be used with a natural horizon by depressing the mirror (M), which reflects the bubble through the horizon glass (H) to the telescope (T).

The bubble is contained in an ordinary spirit-filled tube set into the metal tube (B), which is mounted rigidly to the frame. For day observations, the light entering through the bottom of the tube is sufficient to make the bubble visible to the observer. At night the lamp (L) is used to illuminate the bubble. In order to bring the image of the bubble to a focus at the same point as the image of the celestial body, a half lens is used to focus the rays of the former while the rays from the body pass through the open half.

A convenient means is provided for making the first rough setting of the arm (A). Underneath the arc which carries the scale is a rack into which fits a worm gear operated by the micrometer head (D). By moving the lever (L_1) down, the worm gear is taken out of mesh with the rack and the arm can be set to its approximate position. The lever is then released, the worm gear again meshes with the rack, and the fine adjustment is made with the micrometer head. The head reads directly to the nearest 30 seconds. A lamp (L_2) is used to illuminate the scale at night.

The switch (S) is used for the lamp (L_2), which illuminates the scale, while the lamp (L), illuminating the bubble, is operated by the push button (P). These two switches are located on the handle of the sextant, where they can be operated by the fingers of the hand holding the instrument. The handle contains the battery used for the lamps.

With this instrument, the images of the bubble and the celestial body move in the same direction when the sextant is inclined longitudinally.

Willson bubble sextant.—A similar form of bubble sextant (fig. 16B) has been designed by R. W. Willson, of Harvard University. The bubble level in this case is of the spherical type, so that the leveling of the sextant laterally is facilitated. In the latest model of this instrument the focal lengths of the eyepiece, the objective, and of a lens just over the bubble and the radius of curvature of the spherical surface of the bubble tube are so arranged that the images of the bubble and of the celestial body move the same amount in the same direction for a given inclination of the axis of the telescope. The two images may not move at the same rates; actually the bubble appears to move faster than the object in the instruments which the writer has so far examined. The motion of the bubble can be slowed down by the use of a more viscous liquid, but such a liquid would be seriously affected by low temperatures.

In the Willson sextant the bubble is contained in the lower portion of the vertical tube (B) attached to the telescope. An electric lamp (L) is mounted at the top of this tube to illuminate the bubble at night. A cap with a small central hole is placed just under the lamp to limit the illumination when sighting on a star. If this cap is removed, the illumination from the lamp is suitable for sun observations, or if both the lamp and the cap are removed, the light from the sky is sufficient.

The rays of light pass through the bubble tube, and then are reflected to the eye from a semisilvered surface set at 45° to the axis of the telescope. The rays from the object pass through this surface on their way to the eye.

The arm of this sextant is controlled by a rack, worm gear, and micrometer head, reading to 30 seconds of arc, just as described for the Byrd sextant. A lamp (L′) is provided for illuminating the scale at night.

The two lamps are controlled by two push buttons (P) conveniently situated on the handle (H) of the sextant. A battery is set into the handle to furnish power for the lamps.

The sunglasses (S) should be placed in front of the horizon glass (G) in order to shut out the view through the unsilvered portion of this mirror. This instrument can be used as an ordinary sextant by turning the sunglasses behind the horizon glass down out of the way and using a natural horizon instead.

Schwartzchild bubble sextant.—This sextant (fig. 16C), of German origin, was loaned by the United States Coast and Geodetic Survey for examination in connection with this report. The bubble is of the ordinary tube type and is located just above the lamp (L) in the case (C). The rays of light from the bubble are reflected through the hole in the horizon glass (G) to the eye. For day observations, the lower portion of the case (C) can be folded back as shown in the figure, and the white celluloid reflector (W) used to illuminate the bubble by means of ordinary daylight. For night observations, the bottom of the case is folded down so as to inclose the lamp. A shield in front of the lamp prevents the direct rays of the latter from reaching the bubble. Only the rays reflected from the sides illuminate the bubble so that the intensity is reduced.

The battery for the lamp is contained in the handle (H). The current is turned on by means of a plug at the end of the handle hidden behind the case (C). This plug is arranged with a variable resistance, so that the current flowing depends on the amount which the plug is pulled out.

The images of the sun and bubble move in the same direction when the inclination of the sextant is changed and the image of the bubble moves at approximately the same rate as that of the sun.

The arm is set by means of the rack (R) and a pinion operated by the knurled head (K). A vernier (V), reading to single minutes, is mounted on the arm.

R. A. E. bubble sextant.—This instrument (fig. 17) was designed by the British Royal Aircraft Establishment. For sun observations the eye is usually placed at (E_1). The rays from the sun are reflected from the sunglass (S), while the rays from the bubble pass through both the mirror (M) of plain glass and the sunglass. For star observations, the sunglass is rotated back out of the way and the eye is placed at (E_2). The rays from the star then pass directly through the mirror to the eye, while the rays from the bubble are partially reflected by the mirror.

The bubble level (B) is of the spherical type. The lamp (L) provides the illumination for the bubble and the rays are reflected by the prism (P) up through the lens system to the mirror.

The lamp (L_1) illuminates the scale which is on the large knurled head (H). The batteries for the lamps are in the handle of the sextant and are operated by push-buttons located conveniently on the handle.

It is claimed[11] that the focal lengths of the lenses and the curvature of the upper surface of the level are such that the bubble appears to move with the sun or star when the sextant is tipped, thus facilitating observations.

A later model of this instrument includes a number of improvements, including a vapor bubble and a handle mounted on the side of the sextant. The vapor bubble is formed by filling completely the bubble tube and adjusting chamber with the liquid used, and then increasing the volume of the chamber. Since the liquid is unable to expand to fill the increased volume, a bubble is formed which is filled with vapor from the liquid.

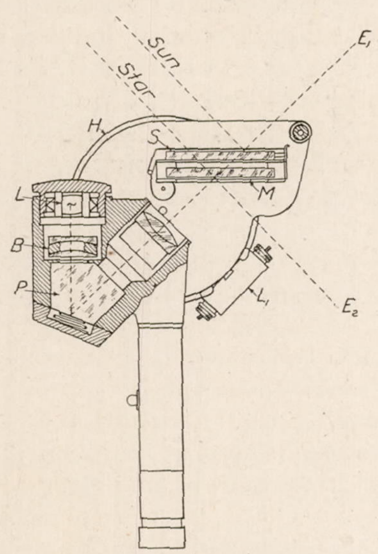

FIG. 17.—R. A. E. bubble sextant.

PENDULUM SEXTANT.

As yet the pendulum sextant has not been utilized in aerial navigation to the same extent as has the bubble type. Several such instruments have been constructed, however, and used successfully on the ground. In at least one case the extreme delicacy of the mechanism is a handicap as regards aerial work.

As a matter of historical interest attention is called to the fact that a sextant utilizing a pendulum artificial horizon was carried on the dirigible *America* when Wellman and Vaniman attempted to cross the Atlantic in 1910.[12]

Pulfrich sextant.—This instrument has been developed by Dr. Carl Pulfrich, of Jena. The telescope is mounted on the arm which moves over the graduated sector, and the whole is so balanced on a pivot that the arc always hangs in exactly the same position regardless of the position of the arm. The telescope is pointed directly at the celestial object. A reflecting prism covers a portion of the field, so that two images of the body are seen—one direct and one reflected. As the instrument oscillates, the two images move in opposite directions and, when they are momentarily in coincidence, the pressure of a finger on a spring stops the oscillation and the reading can be taken. It is claimed that this sextant is both accurate and light in weight.

GYROSCOPIC SEXTANTS.

Two French gyro-sextants are available for use in aerial navigation.

Fleuriais sextant.—This instrument (figs. 18 and 19) was developed some years ago for use in the French Navy by Admiral Fleuriais.[13] It consists of a sextant of the usual form with a gyroscopic horizon attached directly behind the horizon glass.

The horizon is mounted on the upper surface of a wind-driven gyroscope (G), about 2 inches in diameter, which is inclosed in a case. (See fig. 19.) Air is sucked out of the case by means of a pump. Atmospheric pressure then forces air into the case through a small hole so arranged that the air stream impinges upon vanes arranged around the circumference of the gyro, which is thus driven at a high rate of speed. When the gyro has attained the proper speed, valves are closed so as to seal the case hermetically. This is done in order to reduce air friction, so that the gyro may not slow down too much while the altitude is being measured.

[11] "Design of Instruments for the Navigation of Aircraft," by G. M. B. Dobson, Geographical Journal Vol. LVI, No. 5, p. 370, November, 1920; Royal Geographical Society of London.

[12] "The Aerial Age," loc. cit.

[13] "The Search for Instrumental Means to Enable Navigators to Observe the Altitude of a Celestial Body when the Horizon is not Visible," by G. M. Littlehales. Proceedings U. S. Naval Institute, vol. 44, No. 8, August, 1918. Also "Gyrostatics and Rotational Motion," by Andrew Gray, p. 129.

The horizon consists of a series of equally spaced horizontal lines engraved on a glass plate (H), the central or horizon line more prominent than the others. Rays of light from these lines are made parallel by means of a plano-convex lens (L) so that the lines can be brought to a focus in the plane with the image of the celestial body. As the horizon system rotates with the gyroscope at a high rate of speed, the persistence of vision makes it appear to the observer that he is viewing a fixed horizon.

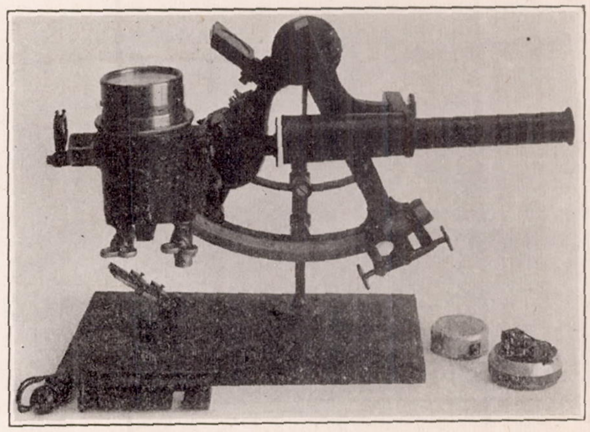

FIG. 18.—Fleuriais gyroscopic sextant.

The image of the celestial body is superimposed on the image of the system of horizontal lines as shown in figure 19. As the gyro precesses, the image of the body appears to oscillate up and down between the lines on the glass. The mean position can be estimated and the reading of the arc corrected accordingly.

Derrien sextant.—This is a French sextant (fig. 20) utilizing a gyroscope to furnish an artificial horizon. A telescopic line of sight (T) is mounted rigidly to the frame. The movable arm (A) carries a horizon glass (H) and a gyroscope (G). The latter has a mirror (M) mounted horizontally on its upper surface. The gyroscope serves to keep the mirror (M) horizontal when taking observations.

The operation of this sextant is very simple. The telescope is pointed directly at the celestial body, and the rays of light pass through the unsilvered part of the horizon glass. Rays of light from the object are also reflected as shown in the figure from the gyro mirror, which is horizontal. However, these rays will not be reflected by the horizon glass parallel to the direct rays unless the horizon glass is horizontal, or, in other words, parallel to the gyro mirror. So the arm (A) is moved until the direct and reflected images coincide, when it is known that the horizon

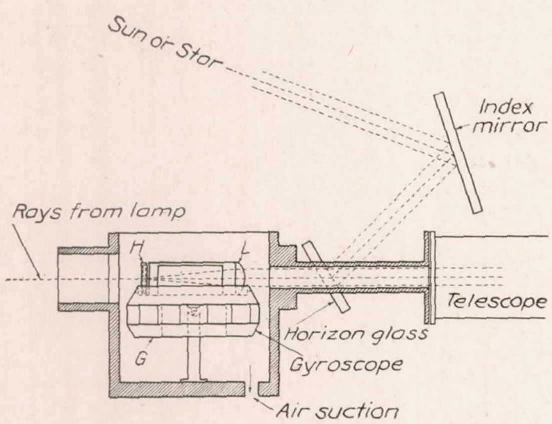

FIG. 19.—Diagram of Fleuriais sextant.

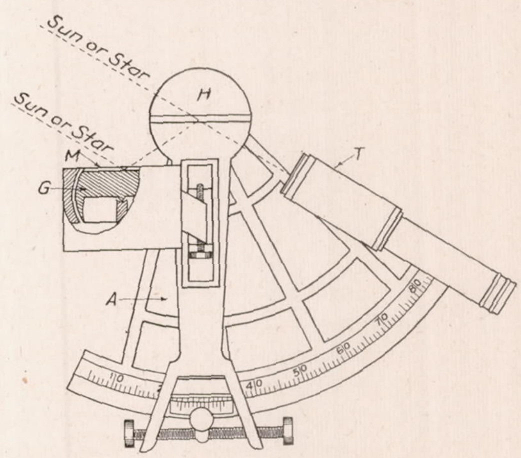

FIG. 20.—Derrien gyroscopic sextant.

glass is parallel to the gyro mirror. The altitude of the body can then be read. The graduations on the scale are equal to the actual angular distances on the arc instead of being compressed to one-half the true length, as in most sextants.

ACCURACY OBTAINABLE.

The question next arises as to what accuracy can be obtained in determining one's position by sextant observations from the air and what accuracy is essential. In the first place, it should be realized that the aerial navigator need not know his location as exactly as the mariner must.

The aircraft is in general not subject to dangers from shoals and hidden rocks, and its superior speed makes an error of from 10 to 20 miles at the end of its journey of little moment, since that distance represents a flight of only a few minutes. For finding the exact location of the landing field other methods are available, and so we can consider that an error of from 10 to 20 nautical miles, corresponding to the same number of minutes of arc, can be permitted.

The usual errors (not including the known corrections for semidiameter and parallax) which may affect the measurement of altitudes with the sextant are (*a*) dip, (*b*) refraction, (*c*) index error, (*d*) bubble error, and (*e*) acceleration errors. It should be observed that the artificial horizon sextant has no dip error, while, on the other hand, the marine sextant can have no bubble error.

(*a*) *Dip.*—The nature of the dip error has already been discussed and it has been pointed out that the dip in minutes of arc may be taken equal to the square root of the height in feet of the aircraft above the horizon used. Terrestrial refraction is included in the law, as above stated, as has been determined by tests made at altitudes up to 12,000 feet.

(*b*) *Refraction.*—Astronomical refraction makes the observed celestial body appear nearer the zenith than it actually is, except in the limiting case, when the body is at the zenith. The magnitude of this error increases as the altitude of the body decreases. Assuming that there will be no occasion to measure altitudes less than 20°, the maximum value of this error is found to be slightly greater than 2.5 minutes. This is for an observation made at sea level, but at 12,000 feet the refraction error is less than 2 minutes. At an altitude of 45° there exist corresponding errors of approximately 1 minute at the ground and 30 seconds at 12,000 feet. For most aerial work this error can then be neglected.

(*c*) *Index error.*—This error occurs if the horizon glass is not exactly parallel to the index mirror when the vernier reads zero. The magnitude of the error can be determined by sighting on a distant object and bringing the direct and reflected images into coincidence. The vernier should then read zero, and if it does not, the reading as thus determined should be subtracted from any altitude measured subsequently.

(*d*) *Bubble error.*—This error is due to the line of sight not being horizontal when the bubble is in the center of the tube. Its magnitude can be determined while the observer is in the air by measuring the dip of the horizon from a known height and comparing the value thus obtained with the true value. The index correction must be applied to the measured dip before comparison with the true dip. Both the bubble and the index errors should be determined for each flight.

(*e*) *Acceleration error.*—Errors due to acceleration are of primary importance when an artificial horizon is used. Only by the best piloting can satisfactory results be obtained. The oscillations of the craft affect the pendulum or the bubble, and if the latter should happen to have about the same period as that of the oscillations of the plane, resonance occurs, and it is hopeless to try to get a reading. It has been reported from the United States naval air station at Pensacola, Fla., that students undergoing NC training have taken sights, using the bubble, with an average error of about 8.5 minutes, and a maximum error which is rarely greater than 15 minutes. If these results represent average conditions, they are excellent. Russell (loc. cit.) reports errors in single readings of from 12 to 14 minutes, using a Willson bubble sextant under what are probably typical flying conditions.

Other less important errors due to the bubble are caused by vibration of the aircraft, unsteadiness of the observer's muscles, and surface tension which may cause the bubble to stick and then move suddenly. Vibration makes it difficult to determine the tangency of the celestial body or its coincidence with the bubble and shakes the liquid in the tube. Unsteadiness of the muscles may be at least partly remedied by a support of some kind attached to the body of the observer.

It is obviously impossible to predict exactly what errors may be reasonably expected under various conditions of flight using different types of instruments. Nevertheless, it is believed that an estimation of the errors involved based on available data may be useful.

Error of a single observation.			Dip error.
	Good piloting.	Ordinary piloting.	
Naval sextant—Sea horizon	2 to 4 minutes		2 to 4 minutes.
Naval sextant—Level cloud horizon	do		Do.
Naval sextant—Average cloud horizon	15 minutes		Do.
Naval sextant with auxiliary artificial horizon	15 to 20 minutes	40 minutes+	
Bubble sextant	10 to 15 minutes	do	
Gyroscopic sextant	No data		

The above table emphasizes the fact that the ordinary sextant used with a horizon which is known to be level is superior to an instrument utilizing an artificial horizon. It is doubtful whether increased accuracy can be attained by taking a series of observations on a cloud horizon, as the error is usually largely due to the clouds not being exactly level. When an artificial horizon is used, however, no single reading should be relied on unless it is impossible to take a series of observations, since in this case the errors are largely due to accelerations of the craft.

CHRONOMETERS.

While chronometers are among the most essential instruments used in aerial navigation, they are so common a type of instrument that no description will be given here. It is advisable to carry at least two chronometers on board the craft, one keeping sidereal time, the other solar time, both for the meridian of Greenwich. The chronometer keeping solar time may be set either to apparent or to mean time. In the former case a slight error will be involved owing to the continual variation in the equation of time, but in the case of flights which last for less than 24 hours this error will be small.

Extreme accuracy in the chronometers is not essential where time signals can be picked up by wireless. If these are not available, it will be advisable to carry a standard chronometer with which the other two can be compared.

REDUCTION OF OBSERVATIONS.

PRECOMPUTATION.

Computation in the air is always difficult, except possibly in the case of a large dirigible. In an open airplane, the force of the wind, the necessity for wearing gloves in most cases, and the speed with which the results must be obtained make quick methods for determining the geographical position of the aircraft from the measured altitude an absolute essential.

Under such circumstances it is often advantageous to compute the altitude and azimuth of the sun, or of any other celestial body which is likely to be used, for certain assumed positions of the aircraft which can be predicted in advance. These positions correspond to the dead reckoning position assumed in the St. Hilaire method, and while they may be in error by from 50 to 100 miles, this fact will have little effect upon the accuracy of the result provided a suitable map is used for plotting the position of the craft. The altitudes and azimuths of the body as it would be seen from each assumed position are computed and tabulated in convenient form for different times during an interval which is so chosen as to include the time when the aircraft will pass near the point.

The work involved in plotting the position can be partly anticipated by drawing from the assumed positions radiating lines in the direction of the sun's azimuth as computed for various times.

The work which must be performed in the air is then very simple. The altitude of the body is measured, the difference in minutes of arc between the measured and the computed altitude is laid off in nautical miles along the proper azimuth line as determined from the table, and a line drawn at right angles to the azimuth line through the point so formed is the desired line of position.

COMPUTATION IN THE AIR.

Precomputation will not always serve one's purpose on account of weather conditions which prevent observations at the proper time on the body whose altitude has been computed. Consequently much effort has been made to provide suitable means, graphical or mechanical, to make any desired computation in the air. A description of these methods will be included in the discussion of the reduction of observations which follows.

The fundamental equation to be solved in reducing an observation is

(*a*) $\sin h = \sin L \sin D + \cos L \cos D \cos t$

where L is the latitude of the observer,
h is the altitude of the celestial body,
D is the declination of the celestial body,
t is the hour angle of the celestial body.

For convenience in computation this can be transformed to the cosine-haversine form, in which all the quantities are positive and the chance of error is thereby reduced.

(*b*) $\text{hav } Z = \cos L \cos D \text{ hav } t + \text{hav } (L \pm D)$

where Z is the zenith distance of the celestial body
and the haversine is defined as the sine squared of one-half the angle.

The reduction of astronomical observations in aerial navigation may be accomplished in four distinct ways:

1. Logarithmic computation.
2. Use of tables.
3. Graphical methods.
4. Use of mechanical calculators.

LOGARITHMIC COMPUTATION.

Equation (*a*) is probably the most useful for logarithmic computation, as the ordinary trigonometric tables can be used. Aerial work, however, does not warrant this high degree of accuracy, which can be attained only by a comparatively laborious process.

USE OF TABLES.

For the more accurate work required in the air, special tables can be used, such as the "Altitude, Azimuth, and Line of Position Tables," published by the United States Hydrographic Office. These tables contain all that is necessary to determine the altitude and the azimuth, the former accurate to one minute of arc.

The reduction may be made by the use of the double entry "Altitude and Azimuth Tables" of de Aquino. These tables, which may also be found in the above-mentioned publication of the Hydrographic Office, avoid the necessity for logarithmic computation, but involve more chances of error.[14]

The altitude and azimuth of the celestial body may be obtained from Hydrographic Office Publication No. 201, "Simultaneous Altitudes and Azimuths of Celestial Bodies." These tables give simultaneous values of altitude and azimuth for celestial bodies having declinations within the range $\pm 24°$ and for latitudes up to 60° north and south. When using these tables the observer often finds it possible to assume his D. R. position on an even degree of latitude and in such a longitude as will make the hour angle of the observed body a multiple of 10 minutes from his meridian, and so can reduce the labor of interpolation to a minimum.

The Hydrographic Office is preparing tables for use in aerial navigation comprising simultaneous values of the hour angle and azimuth of the celestial body for values of the latitude of the observer and the declination of the observed body. These tables allow of a quick determination of the Sumner line with very little interpolation.

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[14] "Simplified Navigation," by Charles Lane Poor.

GRAPHICAL METHODS.

Altitude, azimuth, and hour-angle diagram.—Littlehales has made use of the haversine formula for solving the astronomical triangle graphically.[15] This form of the equation is

$$(c)\ \text{hav}\ Z = \text{hav}\ (L \pm D) + [\text{hav}\ (180° - (L + D)) - \text{hav}\ (L - D)]\ \text{hav}\ t$$

The quantities involved in this equation have already been defined.

If we now let—

$y = \text{hav}\ Z$

$x = \text{hav}\ t$

$a = \text{hav}\ (L \pm d)$

$$m = \frac{\text{hav}\ (180° - (L + d)) - \text{hav}\ (L - d)}{\text{hav}\ 180°}$$

equation (c) can be written in the form

$y = mx + a$

which is the equation of a straight line in terms of its slope and its intercept on the Y axis.

A diagram is now prepared as shown in figure 21 with the haversines of angles from 0° to 180° laid off along the X and Y axes, representing hav t and hav Z, respectively. Now, if we lay off on OY hav $(L - d)$ and on $O'\ Y'$ hav $[180° - (L + d)]$ and connect these points by a straight line, we can immediately solve for t when Z is known, or vice versa.

To do this, we project up from the proper value of t on the X axis to the line just drawn and from this intersection project across to the Y axis where the value of Z may be read.

A relation analogous to equation (c) connecting the azimuth and polar distance $(90° - D)$ exists and may be solved by the same diagram as that for the zenith distance and hour angle.

We have —

$$\text{hav}\ (90° \pm D) = \text{hav}\ (L - h) + \{\text{hav}\ [180° - (L + h)] - \text{hav}\ (L - h)\}\ \text{hav}\ A.$$

Where A is the azimuth of the celestial body and the other quantities have already been defined.

By laying off $(L - h)$ and $[180° - (L + h)]$ in place of $(L - D)$ and $[180° - (L + D)]$ and proceeding as before we can determine the azimuth if the polar distance is given or vice versa.

ILLUSTRATIVE PROBLEM.

Latitude by D. R. = 50° N.

Declination of star = 30° N.

Computed hour angle of star = 105° = 7 hours.

Measured altitude (corrected) 13° 56′.

(a) Altitude:

$$L + D = 80°,\ L - D = 20°.$$

Laying off $(L + D)$ on the $O'Y'$ scale, $L - D$ on the OY scale, connecting these points with a straight line, projecting up to this line from $t = 7$ hours on OX, then from this intersection projecting horizontally to OY we find

$$Z = 76° \text{ or } h = 90° - 76° = 14°.$$

(b) Azimuth:

Using the value for the altitude as just found, we obtain $L + h = 64°$, $L - h = 35°$, also $90° - D = 60°$.

Laying off $L + h$ on the $O'Y'$ scale, $L - h$ on the OY scale, connecting these points with a straight line, projecting horizontally from $(90° - D) = 60°$ to this line, then projecting down from this intersection we obtain $A = 59°\ 45'$.

We now have the information necessary to draw the Sumner line on the map.

Accuracy.—This diagram, if so constructed 15 inches square, will give an accuracy of from 5 to 10 minutes of arc.

[15] "Altitude, Azimuth, and Hour-Angle Diagram," by G. W. Littlehales. Proceedings U. S. Naval Institute, November, 1917.

Rotation of astronomical triangle.—Suppose, for the moment, that we have available a sphere with hour circles and the equator drawn upon it (fig. 22). The hour circles will be graduated from 0° at the pole to 90° at the equator and the equator will be graduated from 0° at one intersection of the meridian, which will be taken as the meridian of the observer, in both directions to 180° at the other intersection of the same meridian with the equator.

Now, in figure 22, let (P) be the pole; (Z) the zenith of the observer; (S) the celestial body; (PD), (PS), and (PC) three hour circles, (PD) being also the meridian of the observer, and (DCB) the equator. (PZS) is the astronomical triangle which is to be solved for (ZS) the zenith distance and angle (PZS) the azimuth of the body.

Let us now rotate the astronomical triangle about the equatorial axis (AB), which is perpendicular to the plane of the observer's meridian, by sliding it over the surface of the sphere, the side (ZP) remaining in the observer's meridian until (Z) coincides with the pole (P) of the sphere. (S) rotates into the point (S′), and since the angle (PZS) is unchanged by the rotation, (P′PS′) is equal to (PZS). But we can read the angle (P′PS′) from the grad-

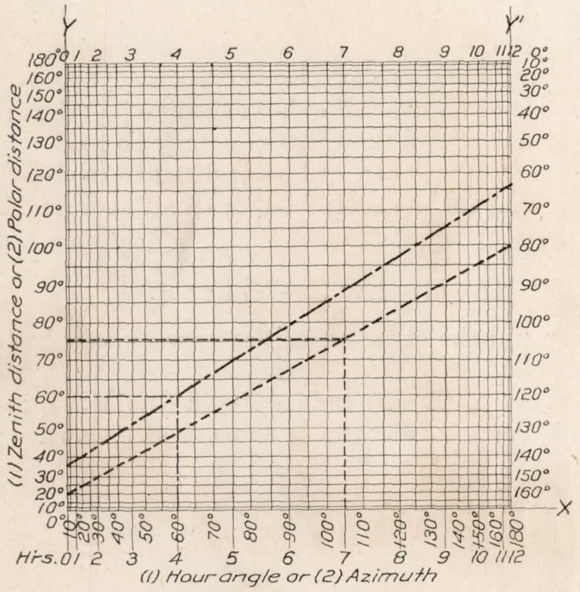

FIG. 21.—Altitude, azimuth, and hour-angle diagram.

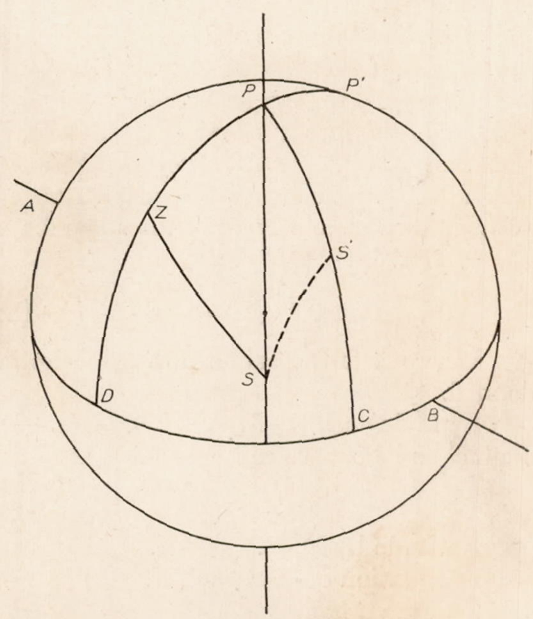

FIG. 22.—Rotation of spherical triangle.

uated equator, for the sides of the angle lie along hour circles. We can also read the arc (PS′) from the graduated hour circle (PC). The desired quantities have thus been found.

To obtain the necessary accuracy, it would be necessary to use a sphere or a portion of a sphere from 10 to 15 feet in diameter. This is plainly impracticable. Consequently several methods have been devised for performing the rotation of the triangle on a projection of the sphere instead of on the sphere itself.

Littlehales method.—Littlehales has used stereographic meridian projection for this purpose.[16] Figure 23 shows the stereographic projection of the hemisphere determined by the observer's meridian (DZPP′) and including the astronomical triangle upon the plane of this meridian. (PZ) is the colatitude of the observer, (PS) the codeclination of the celestial body, and (ZPS) the hour angle of the body. We are to determine (ZS) the zenith distance and angle (PZS) the azimuth of the body.

To do this we rotate the astronomical triangle upon the projection just as we did upon the sphere. This is made possible by superimposing upon the system of meridians and parallels of latitude a network of equally spaced concentric circles drawn about (O), the center of the

[16] "Altitude, Azimuth, and Geographical Position," by G. W. Littlehales. Published by Lippincott.

projection, and of radial lines through (O). It should be observed that (O) is the projection of the equatorial axis (AB) of the sphere (fig. 22). The system of circles is numbered consecutively from the center (O) to the bounding meridian of the projection, and the radial lines are marked by numbers which indicate their angular distance in minutes of arc from the meridian (ON).

In practice it is merely necessary to rotate point (S). Note the numbers of the radial and the circumference passing through (S). Add to the number of the radial the colatitude (ZP) in minutes of arc to find the radial upon which (S′), the rotated position of (S), will lie. Find the intersection (S′) of the new radial with the same concentric circle that passes through (S). The rotation is now completed and the azimuth (P′PS′) and the zenith distance (PS′) can be read from the graduated arcs.

To attain the necessary accuracy, the projection has been made for a sphere 12 feet in diameter. The projection is subdivided into 368 overlapping sections, which are numbered in order and arranged in a compact form. A key diagram is provided showing the whole projection with its subdivision into sections. In this way the navigator can easily observe in what sections the points (S) and (S′) lie, and can turn to the corresponding plates in order to read off the desired values.

In figure 23 the meridians and parallels of latitude are shown as full lines. The superimposed network of concentric circles and radials used for performing the rotation is shown in light dash lines in the upper half of the projection. The astronomical triangle is shown in its original position in heavy full lines; it is shown in its rotated position in heavy dash lines. The subdivision of the projection into overlapping sections is not indicated in the figure as the addition of another system of lines would be confusing.

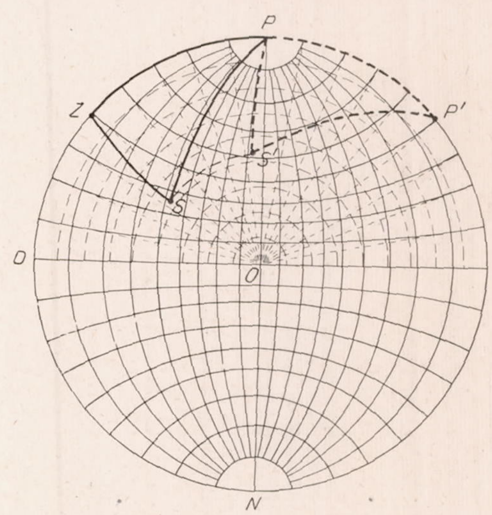

FIG. 23.—Littlehales diagram.

Veater diagram.—Commander Veater, of the Royal British Navy, has used the Mercator projection for this same purpose.[17] The observer's meridian is taken as the equator of the projection. Thus rotation about the equatorial axis AB of the sphere (fig. 22) becomes translation parallel to the observer's meridian.

Here, as in the Littlehales method, the projection is subdivided into a larger number of overlapping plates and a key diagram to these plates is provided.

MECHANICAL DEVICES.

Line-of-position computer.—This slide rule (fig. 24), designed by Charles Lane Poor, for solving the cosine-haversine formula, is in the form of a circular metal plate engraved with a group of scales necessary to solve for the altitude and azimuth. This plate is surmounted by a movable celluloid disk carrying a radial reference line and by an arm which can be rotated to any point on the circumference of the disk and clamped there. The instrument gives an easy and rapid reduction, one which is amply accurate for aerial work. A description of this computer and its use and a comparison of the results obtained by the logarithmic, Aquino, and mechanical methods is to be found in "Simplified Navigation" (loc. cit.).

Bygrave slide rule.—A description of the construction and use of this computer can be found in "Air Navigation" (loc. cit.). The slide rule is designed to solve the two right-angled spherical triangles into which the astronomical triangle can be divided. It is in the form of two concentric cylinders, about 6 inches long and 3 inches in diameter, each carrying a spiral scale. It is claimed that an accuracy of one minute of arc is attainable in nearly all cases.

[17] "Air Navigation," loc. cit.

Nomogram slide rule.[18]—A slide rule for solving the formula on which the altitude, azimuth, and hour-angle diagram is based has been devised by Wimperis and Horsley. The name of the slide rule is explained by the fact that the British use this same diagram under the name of the "Spherical Triangle Nomogram."

Mechanical navigator.—Instruments which are mechanical representations of the celestial sphere have been built to solve either a single astronomical triangle or two triangles simul-

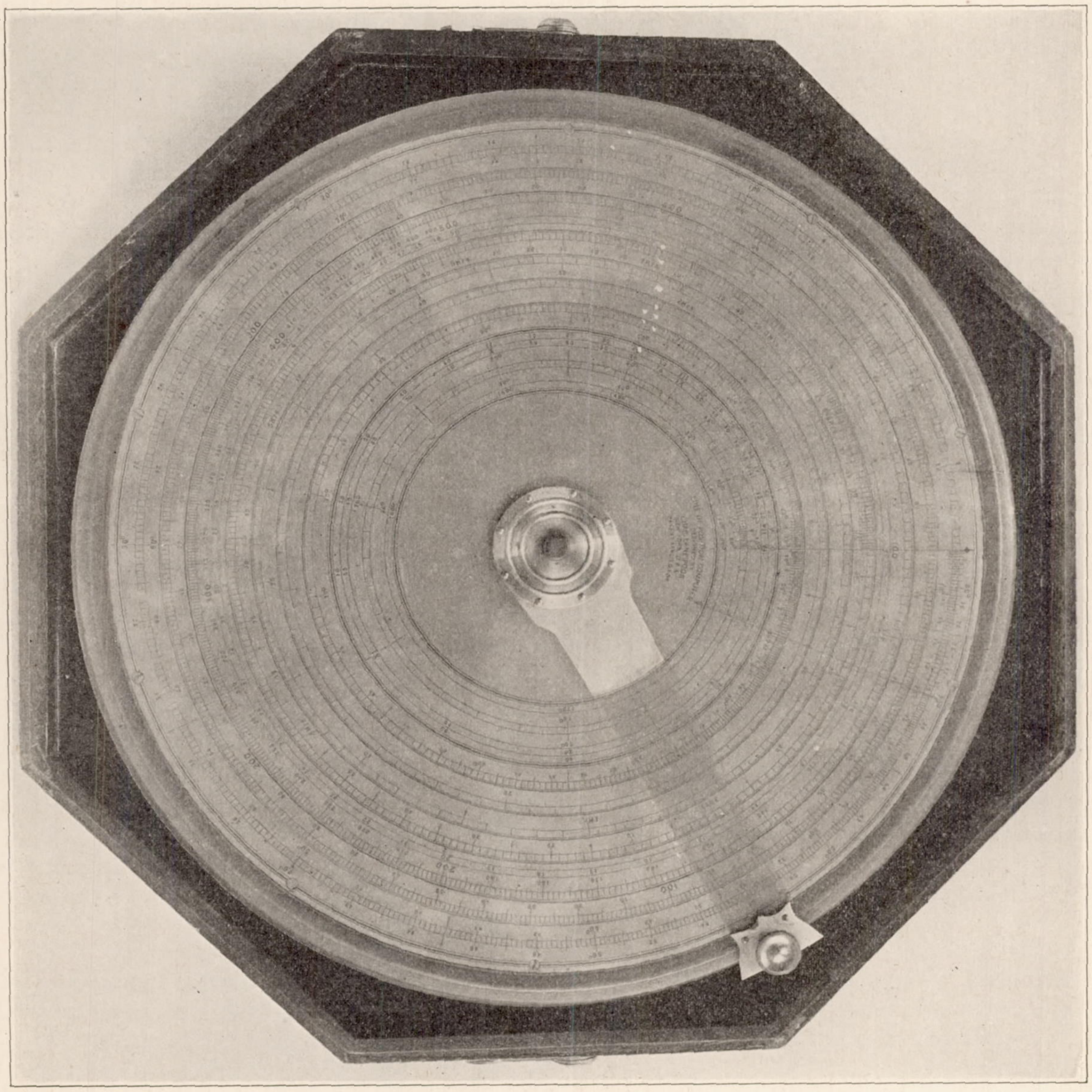

FIG. 24.—Line-of-position computer.

taneously. Graduated circles which can be turned and rotated with respect to each other represent the equator, the meridians of the observer and the celestial body, and the great circle passing through the positions of the observer and the celestial body. Verniers are provided for reading the angles.

In one instrument of this type which the writer examined the verniers read to 30 seconds of arc. It was clear that if the required accuracy were reduced to, say, three minutes of arc,

[18] "Air navigation," loc cit.

which is sufficient for aerial purposes, the instrument could be sufficiently reduced both in size and weight for use on dirigibles.

METHODS OF PLOTTING POSITION.

The usual method of plotting position has already been described. The dead reckoning position is plotted on the map, a line is drawn through this point in the computed direction of the sun, the difference between the observed altitude and the computed altitude in minutes of arc is laid off along the azimuth line in nautical miles. If the observed altitude is greater than the computed, the true position is nearer the geographical position of the sun than the assumed dead reckoning position. A line drawn through the point thus found perpendicular to the azimuth line is the desired line of position. If we have an observation on only one body, the intersection of the azimuth line and the line of position is the most probable position of the craft.

Littlehales method.—Littlehales has originated a simplified method of plotting position.[19] He selects a suitable position within the limits of the chart and computes the simultaneous altitudes and azimuths of selected celestial bodies as they would appear if viewed from the chosen position at definite intervals of time. These quantities are tabulated for use in the air.

The observer, knowing himself to be within the limits of his map, measures the altitude of one of the selected celestial bodies. Comparing the measured altitude with the altitude computed for the body at the given instant if viewed from the chosen position on the map, he may find a difference as great as several degrees, depending on the area of the earth's surface included in his map. He measures off along a line drawn through the chosen point in the direction of the celestial body a distance which equals in nautical miles the altitude difference expressed in minutes of arc. Then he knows himself to be on the line of position drawn through the point so found perpendicular to the azimuth line.

Figure 25 is a representation of the earth. The area included in the rectangular figure (MM′NN′) is that included in the observer's map. (O) is the chosen point of this area for which the simultaneous altitudes and azimuths are calculated. A compass diagram is drawn with (O) as center to facilitate laying off the azimuth line for the body the altitude of which is to be measured.

Suppose that at a given instant the altitude of a star whose geographical position is shown at (S_1)is measured. Assume that this measurement gives a zenith distance (S_1A_1) as against a computed zenith distance (S_1O). The observer then takes the difference of the measured and computed zenith distances (or altitudes) and lays off the corresponding distance (OA_1) along the computed azimuth line of the star, measuring toward the star if the measured altitude is greater than the computed, and away from the star if the reverse is true. He knows that he is on the arc of the small circle having (S_1) for center and passing through (A_1). Notice that (A_1), however, is not the most probable position of the craft since (O) was not necessarily the most probable position before the altitude was measured.

If we can measure the altitude of another star whose geographical position is, for example, (S_2), we can establish another small circle, this one having (S_2) for center and passing through (A_2) where (OA_2) is the altitude difference for the second body. The two small circles intersect at (P), which is then the location of the observer.

For ease in plotting position by this method, it is essential that we use a projection by means of which great circle arcs plot practically as straight lines within the required limits. The Mercator projection is not satisfactory for a case where the altitude difference exceeds a few minutes of arc. Littlehales has selected the ordinary or American polyconic projection and the Lambert zenithal projection for this particular use as possessing the desired characteristics. With these projections it is possible to replace the arcs of the circles through A_1 and A_2

[19] "The Chart as a Means of Finding Geographical Position by Observations of Celestial Bodies in Aerial and Marine Navigation," by G. W. Littlehales. Proceedings of the U. S. Naval Institute, March, 1918.

by straight lines without causing too great an error in the position of the intersection. The Lambert zenithal projection was used in the aerial navigation chart of the North Atlantic Ocean which was prepared by Littlehales for use on the transoceanic flight of the United States Navy *NC* boats in 1919.

Favé method.—Favé has used stereographic projection in a way somewhat similar to that described above. He selects the central point of the map as the fixed point for which the simultaneous altitudes and azimuths of suitable stars are computed. He then constructs on a sheet of paper a series of arcs of circles of equal altitudes for the chosen stars. The circles of equal altitudes plot as circles on the stereographic projection. A straight line is drawn through the centers of the arcs.

The map is constructed on transparent paper. It is laid over the paper on which the series of arcs is drawn and is oriented; i. e., it is turned until the straight line through the centers of the arcs becomes the azimuth line for the observed star from the central point of the map. It is then moved parallel to the azimuth line until the altitude circle passing through the central point corresponds to the altitude given by the table. The observer can then trace on the map the required portion of the altitude circle corresponding to the measured altitude to obtain the line on which he is located. Figure 25 will aid in making this method clear.

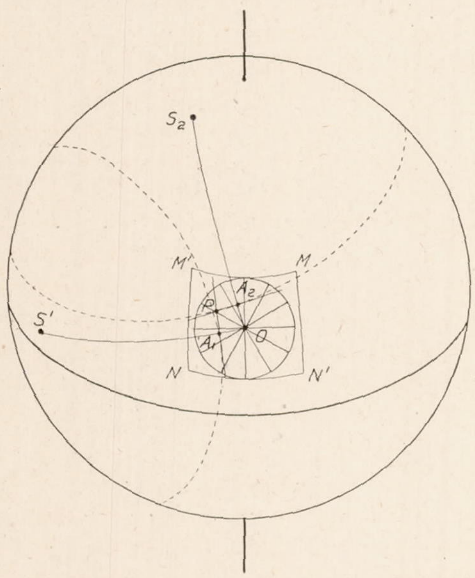

FIG. 25.—Littlehales method of plotting position.

Baker navigating machine.—An instrument for obtaining the curve of position without the necessity of computing an altitude and azimuth has been developed in England.

This machine carries in a case the map of the region over which the flight is to take place with a special chart superimposed on the map and capable of being moved over the latter by means of rollers. This chart carries on its surface lines of equal altitudes for the sun. The equal altitude lines are the Mercator projections of portions of the equal altitude circles which may be imagined to exist on the earth's surface, having for center the subsolar point (assuming the earth to be a sphere). A moment's reflection will make it clear that these circles move westward over the earth as the latter rotates and north or south as the declination of the sun changes. Only the east to west motion is reproduced on the map by sliding the chart over it. Changes in declination cause changes in the spacing of the curves and so it is necessary to make different charts for different declinations of the sun. This has been done from 24° N. to 24° S. by 4 degree intervals. Consequently the declination for which the chart is drawn need never be more than 2° from the true declination. To take account of the small difference which may then exist, a first-order correction is made to the observed altitude by multiplying the difference in the declination by the cosine of the hour angle. This computation is made by means of a slide rule attached to the navigating machine.

The only operations necessary to obtain the Sumner line on the map by this method when the altitude of the celestial body has been determined are to slide a special transparent chart over the map until the proper time as indicated on the time scale of this chart is opposite the meridian, to correct the indicated altitude for the difference in declination (of the chart and the celestial body) by means of a slide rule attached to the machine, and to mark the Sumner line on the map by means of carbon paper.

A chart carrying equal altitude curves for six first magnitude stars has also been prepared for the machine. For stars the change in declination is negligible, so that one chart is sufficient and no correction need be applied.

Brill method.—Brill, in Germany, has used azimuthal (or zenithal) projection in a very similar manner. Brill constructs on a strip of tracing cloth curves of position corresponding to altitudes of selected bodies. This is mounted on rollers so that it can be slid under the map, which is drawn on transparent paper. By orienting the map according to the azimuth taken from the table, and sliding the strip of cloth to a position which depends upon the altitude given by the table, the observer can trace on his map the curve of position corresponding to the measured altitude.

DIRECTIONAL WIRELESS TELEGRAPHY.

The radio direction finder is a recent development which is useful to both mariners and aviators. It will be of particular value in commercial aviation for position determination and for landing purposes.

Previous to the war with Germany a small amount of work had been done toward determining the position of aircraft by means of the directive properties of a radio receiving coil, but it was only during the war that this method came to be used in a practical way.

FUNDAMENTAL PRINCIPLE.

If a rectangular coil is mounted in a vertical plane so that it can be revolved about a vertical axis and its ends connected to suitable receiving instruments, the device can be utilized to determine the direction from which the received waves are coming. The directive properties of the coil can perhaps be most easily understood by considering the effect on the coil of the magnetic force which accompanies the radio waves. This force is horizontal and at right angles to the direction of travel of the waves. Now, if the plane of the coil is parallel to the direction in which the waves are traveling, the coil will be threaded momentarily by magnetic lines of force which vary with the phase of the wave from a maximum in one direction to a maximum in the opposite direction. This change in the magnetic lines of force sets up in the coil an induced current which is a maximum for the assumed position of the coil but which decreases to zero as the latter is rotated until its plane is parallel to the direction of magnetic force, or, in other words, is at right angles to the direction of travel of the waves. This is the fundamental principle involved in the radio direction finder.

METHODS OF USE.

There are two general methods of navigation by means of the radio direction finder. In the first the craft transmits and fixed radio direction finder stations on the ground determine its direction, compute the position, and transmit it by radio back to the ship. In the second method the ship carries its own direction finder, with which it determines the direction of two or more fixed beacon stations, which transmit upon request, or, as will probably be the case in the future, send out signals at regular intervals. The first method is desirable for aerial use, since the apparatus which must be carried is lighter, but it has several disadvantages. As the demands upon the ground stations grow heavy, considerable delay and confusion may be experienced in keeping the necessary number of aircraft informed as to their location. For military use, too, this method is impracticable, since the call for position would immediately reveal the position of the craft to the enemy. The Germans used this method in connection with the Zeppelin raids on England, and consequently the British were able to trace the progress of the big dirigibles as they crossed the North Sea.[2] Present indications are that the future will see the direction finder carried on board the aircraft with beacon stations sending signals at regular time intervals.

A number of modifications of the apparatus for use in the air or on the ocean are possible. It is obvious that either the maximum or the minimum intensity of signal can be used to determine the direction. Theoretically the minimum method is more desirable owing to the fact that the point of extinction of the signal is more clearly defined than the point of maximum intensity. Practically, however, the noise in the receiving set caused by the ignition currents of the engines masks the point of extinction, so that instead of a point a zone of extinction is found. The operator finds the limits of this zone and bisects the angle.

[20] Aeronautical Journal, August, 1919, p. 465.

To overcome this objection to the minimum method, the British have adopted the double-coil aerial. Two coils at right angles are used. The approximate direction is found by means of one coil using the maximum method. Then the second coil is put in the circuit by throwing a switch and, if this coil is not exactly in the position for minimum signal, its effect will be to add or to subtract from the signal received by the maximum coil. If the second coil is in the position for minimum signal, throwing the switch produces no change in the intensity of the signal received on the maximum coil from the direction of which the position of the transmitting station is then noted. It will be observed that this method preserves the sharpness of the minimum method, at the same time yielding a loud signal.

The single-coil system is favored by the United States Naval Air Service. By improved methods of eliminating the disturbances due to the magneto, it has been found possible to use the minimum method with a single coil, this having the advantage of being much more rapid than the double-coil system.

Another modification is possible in the choice of either the fixed or the rotating coil aerial. When the first is used, a large fixed coil is mounted on the wing and the aircraft must itself be turned until it is headed toward the beacon station. This arrangement is particularly useful where it is desired to fly directly toward a particular station. It should be remembered that this procedure will not give the shortest path to the station, as the drift due to the wind will sweep the ship to one side and thus cause it to approach the station following a "curve of pursuit."

A fixed double-coil aerial may be used on the wing in combination with two smaller coils mounted at right angles to one another in the fuselage and within which a small "search coil" is rotated. Rotating the search coil is equivalent to turning the large aerial, but the much smaller size and weight of the former, as well as its sheltered position, make it far easier to manipulate. This arrangement increases the difficulties of tuning.

When the rotating aerial, either single or double, is used, it is mounted in the fuselage.

SOURCES OF ERROR—ACCURACY ATTAINABLE.

It may be said that outside of instrumental errors which can be compensated there are two general sources of error encountered: (*a*) Distortion due to neighboring objects, such as the engine and other metallic parts of the craft, and (*b*) a change in the direction of the advancing wave front owing to atmospheric conditions. Strays and static disturbances may cause a great deal of trouble, but they can hardly be classed as errors. Distortion due to neighboring objects is practically all due to the craft itself when flying. It can be determined by swinging the ship, just as is done in compensating the compass. The atmospheric effect is very marked at night in the case of long wave lengths. Deviations of the order of 90° may occur in the case of very long continuous waves,[21] but this effect is fortunately quite small for the shorter wave lengths which are ordinarily used for radio communication with aircraft.

A difficulty is found in the electrical disturbance caused by the magneto. It has been found necessary to cut out the short wave lengths given off by the latter in order to decrease the noise which these waves cause in the telephones. This may be accomplished by screening the whole magneto system or by reducing the radiating surfaces.

The magneto was a serious source of trouble in the transatlantic flight of the *NC* boats. Owing to the haste with which the project was organized, there was not sufficient time to develop the wireless direction-finding apparatus to the proper point, and, in the case of the *NC-3* at least, it was found impossible to use the system for distances of more than 10 miles because of disturbances caused by the engines.

The British claim to have obtained during a number of test flights an average error of 1¾° in bearing using beacon stations at distances ranging from 20 to 500 miles. This corresponds to an average error in position of 7 miles. The sensitivity of the system was increased to ¾° by

[21] Bureau of Standards Scientific Paper No. 353, "Variation in Direction of Propagation of Long Electro-Magnetic Waves," by Lieut. Commander A. Hoyt Taylor, U. S. N. R. F.

making the area turns on the minimum coil about eight times as great as those on the maximum coil.

For a fuller description of the principles and application of the radio direction finder the reader is referred to the footnotes below.[22]

METHODS OF PLOTTING POSITION.

The charts used for marine navigation are usually based on the Mercator projection. The path followed by the wireless wave reaching the aircraft from a fixed station is the arc of a great circle and, on the Mercator projection, great circles plot as curved lines. So to plot the position of the aircraft the navigator should draw through each fixed station a curve, which is the arc of a great circle and which will have the proper direction at the point finally determined as the location of the ship. There is no direct geometrical solution of this problem known.

Three methods may be used to determine the position: (*a*) A conversion angle may be computed and applied to the observed bearing to get the rhumb line (the straight line joining two points on the Mercator projection), (*b*) the Weir azimuth diagram may be used to plot the position on the Mercator projection, or (*c*) a different projection, such that great circles plot as straight lines, may be used.

(*a*) *Conversion angle.*[23]—A conversion angle may be computed and applied to the bearing of the great circle passing through the fixed station and the craft to give the approximate bearing of the rhumb line through the same two points. This angle, shown in figure 26, is equal approximately to half the difference of the longitudes of the station and the ship multiplied by the sine of their mean latitude. So, by using the dead reckoning position of the craft, the conversion angle can be computed and the rhumb line drawn. A second rhumb line through another beacon station and intersecting the first rhumb line gives the position. This method can be used up to distances of about one thousand miles.

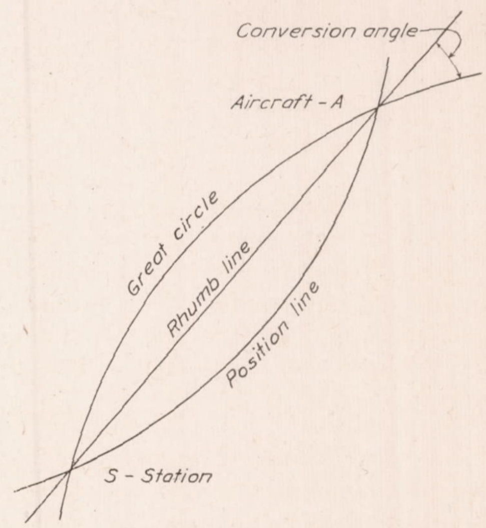

FIG. 26.—Conversion angle.

(*b*) *Weir azimuth diagram.*—In figure 26 are shown the great circle, the rhumb line, and the position line cutting the locations of the beacon station (S) and the aircraft (A) as plotted on a Mercator chart. The position line is the locus of points such that all great circles passing through (S) and cutting this line at consecutive points make the same angle with the meridians through these points. Hence we know that the aircraft is located somewhere on the position line (SA), but we do not know the point on this line. Now, if we obtain another position line from a second station, the intersection of the two will locate the aircraft.

The Weir diagram can be used to facilitate the plotting of the position lines on the Mercator projection owing to the fact that these lines are straight on this diagram. The sending station is marked on the zero hour angle line of the Weir diagram at the proper latitude. A straight line is then drawn from this point with a bearing equal to the observed bearing. The points in which this position line cuts the hour circles and the latitude circles are transferred to the Mercator projection. The line drawn through these points then determines the position line on the latter. Proceeding in the same way, the navigator can draw a second position line on the Mercator chart, and thus determine the position from the intersection of the two.

[22] Bureau of Standards Scientific Paper No. 354, "Principles of Radio Transmission and Reception with Antenna and Coil Aerials," by J. H. Dellinger.

Bureau of Standards publication (forthcoming), "The Radio Direction Finder and Its Application to Navigation," by F. A. Kolster and F. W. Dunmore.

"Direction and Position Finding," by H. J. Round, Journal Institution of Electrical Engineers (British), No. 58, pp. 224–247 and 247–257, March, 1920.

"Wireless Navigation for Aircraft," by J. Robinson, Electrician, No. 83, p. 420, October, 1919.

[23] Air Navigation (loc. cit.).

(*c*) *Gnomonic projection.*—The determination of position by the radio compass may be simplified by use of the gnomonic projection. A gnomonic chart is obtained by projecting points on the earth's surface onto a tangent plane by means of lines drawn from the center of the earth through the points. Thus it can be seen that great circles plot as straight lines on this projection.

Then, if the bearing of the ship is measured from the fixed station, it is simply necessary to plot a straight line through the station with a bearing equal to the observed bearing and it is known that the ship is located on this line. A similar line from another station will give an intersection which locates the ship definitely.

If, however, the bearing of the shore station is measured at the ship the problem is more complicated, since the shore-to-vessel bearing is not the same as the vessel-to-shore bearing on account of the fact that great circles do not cut successive meridians at the same angle. This difficulty has been overcome, it is claimed, in a method devised by E. B. Collins, of the United States Hydrographic Office.[24] He makes use of the gnomonic projection, together with a specially arranged compass diagram for each fixed station, so that the observed bearing can be laid off from the fixed station.

Still another method has been developed by Littlehales,[25] in which the navigator determines a position line by means of an observed vessel-to-shore bearing and two or more assumed latitudes.

Littlehales also points out in his discussion of the method just mentioned that Hydrographic Office Publications Nos. 71 and 120 (Time Azimuth tables) can be utilized to furnish a simple and accurate method of plotting a position line for the ship when the shore-to-vessel bearing from a given fixed station has been determined and transmitted to the ship by radio. The approximate latitude of the vessel will be known, so that certain limiting latitudes can be determined. Then, by the use of the above-mentioned tables, taking for latitude the latitude of the fixed station, for declination the latitude of the vessel, and for azimuth the shore-to-vessel bearing, the hour angle (or longitude of the vessel measured from the fixed station) corresponding to the assumed declination can be read. Thus one point of the position line can be plotted. By determining the hour angles corresponding to the limiting latitudes (or declinations) of the vessel and to as many intermediate latitudes as may be necessary for purposes of plotting, the navigator can obtain a sufficient number of points to enable him to plot the position line.

The use of the gnomonic projection with special compass diagrams appears to be the best for use in aerial navigation. The work of plotting the position line is extremely simple and the map can be reduced to a size which is suitable for use either in airplanes or dirigibles.

[24] "Position Plotting by Radio Bearings," E. B. Collins, U. S. Naval Institute Proceedings, vol. 47, No. 2, February, 1921.

[25] "The Prospective Utilization of Vessel-to-Shore Radio-Compass Bearings in Aerial Navigation." G. W. Littlehales Journal American Society of Naval Engineers, vol. 32, No. 1, February, 1920 pp. 38–44.

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