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THE SPHERANT.

AN INSTRUMENT FOR OBSERVING HOUR ANGLES OR LATITUDE DIRECTLY.

by

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The instrument described in this article has been under development at the University of California for several years. It breaks the two-hundred year old tradition that a navigator, in order to find his position, must measure an altitude and then solve a spherical triangle. The instrument gives directly either hour angle or latitude. The observed hour angle, combined with a proper Greenwich hour angle from a watch or chronometer, yields the longitude. Usually such latitudes and longitudes are not independent but lie along a SUMNER line as in the case of reduced sextant observations. The advantage lies in the elimination of practically all computation or use of tables. The instrument has the same weight as the average sextant, and *with the same amount of practice*, is as easy to observe with. It is called a *Spherant.*

Coming so soon after a remarkable series of developments in nautical tables it may be well to review the differences between the two lines of attack. The considerable number of new tables which have appeared in recent years are designed to give a navigator the solution of an astronomical triangle and thence a line of position with the minimum amount of computation. The entries into the various parts of the tables require little or no interpolation, and these entries can be made, the necessary additions and subtractions completed, and the altitude difference determined, in less than five minutes when one is familiar with their use. These solutions are, therefore, made in about one-fourth of the time required by the old logarithmic methods This saving of time and work is perhaps of no greater importance than the accompanying reduction in the chances of making a numerical error in computation. In some cases the formulas employed have been known for a long time, or the advantages of the particular arrangement or combination may have been predicted. Regardless of such facts, navigators owe their greatest debt to the men who have had the genius, patience and courage necessary to arrange tables in practical form, have them printed and made available. When the history of the subject is written it will show that in recent years there has been a rapid succession of such developments bearing the names of AQUINO, LITTLEHALES OGURA, WEEMS, and DREISONSTOK, together with other developments of less immediate practical importance.

In general, these modern methods are based on the supposition that a navigator with a sextant, *Nautical Almanac*, and Greenwich time chronometer has available the altitude, declination, and Greenwich hour angle. He desires his latitude and longitude, but usually the nearest approach to his desire is a line of position. In the old time-sight method an altitude, declination, and latitude are employed in solving a spherical triangle for the hour angle, which when applied to the Greenwich hour angle gives the longitude. The more modern method involves a reversal of this procedure and employs a declination, and *assumed* hour angle, and an *assumed* latitude in solving a spherical triangle for the altitude. Most of the developments in nautical astronomy have been in the direction of simplifying the solution of this astronomical triangle. Numerous mechanical devices, such as combinations of graduated circles, cylindrical slide rules, and graphical diagrams have been employed but for various reasons have proved to be less satisfactory than tables. The one marked exception is the WEEMS series of star altitude curves for reducing two simultaneous star altitudes.

For two hundred years, then, mariners have been measuring altitudes with sextants. Before this altitude can be of any value an astronomical triangle must be solved. That the methods of solving this triangle have reached a high degree of perfection is indicated above and is well known to all progressive navigators. But is it necessary to measure an altitude at all? Why not measure something more closely related to the desired quantities?

A somewhat neglected line of development in navigation is that of orienting, by means of either gravity or the horizon, and a line in sight to an astronomical body, an instrument so designed that a desired quantity is read directly from a graduated arc, even when this result is an angle between imaginary points in the sky. For example, a surveyor's "solar attachment" places the vertical circle of his transit in the plane of the meridian; the sun compass in the same way indicates the true meridian; and the equatorial mounting of the telescope in an astronomical observatory gives the hour angle and declination of an object. It would hardly be proper to classify such instruments as mechanical methods of solving the astronomical triangle; perhaps "automatic solutions" would be a more nearly correct term, but in all three cases the desired result is obtained directly from the instrument, and, although the result is dependent upon the apparent altitude or zenith distance of the celestial body, these instruments have no arcs corresponding to this side of the astronomical triangle.

To an astronomer the instrument presented here is easily explained by analogy with his equatorially mounted telescope: Suppose that such a mounting is correctly adjusted in azimuth and provided with a graduated arc for measuring the elevation of its polar axis. If a known declination is then set off on the declination circle and the object sighted along the collimation axis, the telescope will give the local hour angle of the body and the observer's latitude. If the telescope and its mounting is then made portable and the pier provided with some kind of a levelling device it can no longer give both latitude and hour angle but will give either one if the other is provided. In doing so the polar axis will automatically be placed in the plane of the meridian. If various values of either latitude or longitude, and hence hour angle, were assumed, such an instrument could give a corresponding value of the other coordinate such that the assumed and instrumental coordinates taken together would be the coordinates of a point on the SUMNER line of position. There is a vast difference between such an uprooted observatory telescope and a practical navigational instrument, but it was along this line of reasoning that development was started. Probably, to navigators not familiar with observatory instruments, the principle is less clear from this explanation than it is from the explanation of the use of the developed instrument which follows later. Many astronomers and navigators have undoubtedly thought of such an application but probably in thinking ahead, several apparently insurmountable difficulties became apparent. The present development was almost given up as hopeless on several occasions, and three different instruments, each of a fundamentally different design, were constructed before anything of a really practical form resulted. Photographs of the three models are shown here and a detailed account of their various characteristics may be published soon in the University of California publication. The present article is limited to a description of the construction, principle, and use of the final form only.

LEVELLING DEVICES.

This instrument, like a sextant, must make use of either the horizon or a levelling means of the "artificial horizon" sort. It was originally planned to construct two kinds of instruments, one for use on shipboard, making use of the horizon, and another equipped with a bubble cell for use in aircraft. There are, however, so many occasions when each method would be of value in the field commonly covered by the other that a system has been worked out whereby in the same instrument either a bubble or the horizon can be employed at will, or both seen at the same time. There is so much confusion among navigators concerning the value of a bubble and so much thoughtless prejudice against "bubbles" even by some naval aviators that the advantages of this combination may in some cases be misunderstood unless further explanation is given.

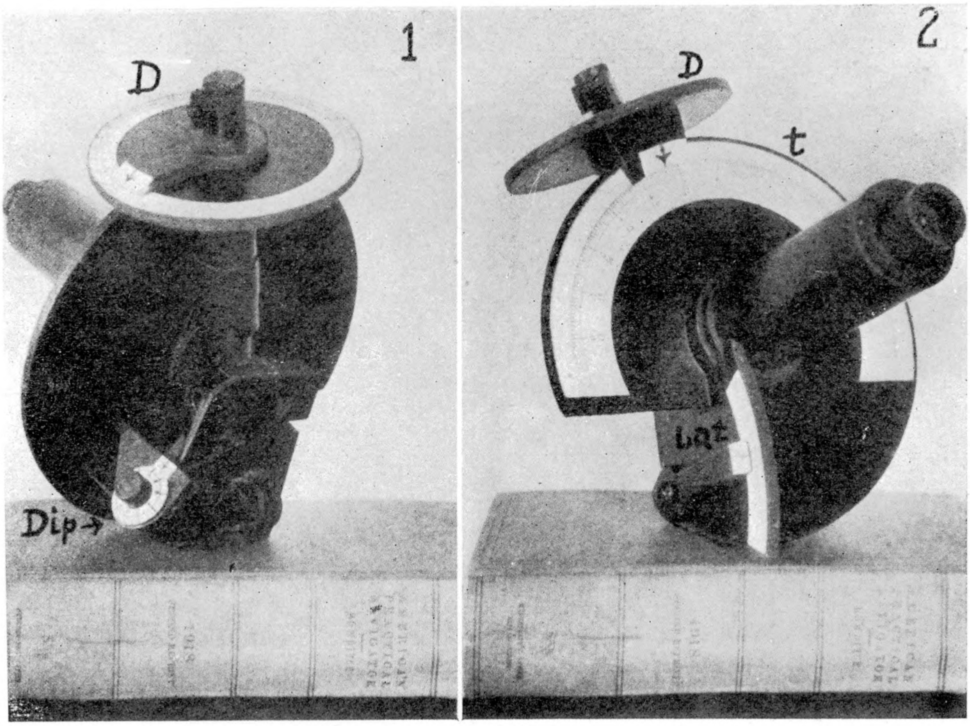
It is true that the irregular horizontal accelerations of a plane may make even the mean of half a dozen bubble-sextant readings uncertain by five to twenty miles, and this makes a poor comparison with the work of the surface navigator who sometimes carries fractions of a mile through his computations. Yet this is all that is ordinarily possible as the horizon is available to a plane only during a small part of the time that celestial bodies are visible. The horizon is lost in haze at a relatively low elevation. Sometimes a horizontal line or two may be seen from a high altitude but these are usually the surfaces of air strata of different characteristics and have unknown dips with respect to the position of the true horizon. To use the horizon then requires coming down close to the surface, a proceeding opposed to one of the first principles of aerial warfare, as well as being an inconvenience. Furthermore, as surface navigators also are aware, the horizon is invisible on many days when the sky is fairly clear but atmospheric visibility low, and it is seldom visible at night. A plane covers ground so rapidly that lack of night (or day) observations would be far more serious than in the case of a ship. A substitute for the horizon is therefore of sufficient importance to justify even considerable loss in accuracy. Considering speed and visibility, ten miles are not of much more importance to the average plane than a mile is to the average ship. The absence of long flights requiring celestial navigation in peace time sometimes obscures the fact that there are some types of military aircraft which in war time must be able to navigate by celestial observations. A great deal of experimenting has been done with pendulums, gyroscopes, spirit levels, etc., and even more remains to be done, but so far the spirit level or "bubble" is the simplest and most satisfactory means. An artificial horizon of this sort makes observations possible at high altitudes, on days when the horizon is indistinct even at the surface, at night when complete fixes are possible, and even from above a cloud layer. It, therefore, makes celestial observations available during a very much greater portion of the time than would be possible with the horizon. The issue of bubble-type instruments to aircraft units is the result of serious study of the problem from the point of view of long-distance military flying.

It quite frequently happens that a bubble can be of considerable value on surface ships. For general all-round navigation a bubble instrument would be of very little value on any type of surface craft. The rolling of a ship ordinarily produces accelerational errors of greater magnitude than those experienced in a plane — especially if the observer ignores the motion of the ship. With a little study of the problem quite different results become possible. A ship has so much inertia in comparison to the forces involved that horizontal accelerations produced by irregular translation of the ship as a whole produce the smallest part of the effect, The greater part of the accelerations comes from rolling and pitching (The reverse is true in air-craft where, furthermore, the observer is never more than a few feet from the centre of rotation). This quasi-periodic motion produces the maximum horizontal acceleration at the instant when the ship is farthest from its normal quiet-water position. It becomes practically zero when the horizontal motion of the observer is the greatest, *i.e.*, when the ship is passing through her level position. By making the coincidence at this point of the ship's motion surprising results can be obtained. The first time the writer attempted to apply this reasoning was on board the *U.S.S. Chaumont* on the afternoon of September 24, 1929, off the coast of California, approximately fifty miles south of San Francisco. Between 3.25 and 3.35 p.m. seven longitudes were observed with a spherant equipped only with a bubble. The average error of a single sight was eight seconds (time) of longitude, or 1.6 miles. The maximum error in the series was fourteen seconds of longitude or 2.8 miles. At the end of each roll the bubble was tight against the side of its cell and by observing at the wrong it could have been truly reported that bubble observations gave errors of about 2°. This was done on a clear California day with an average fairweather sea and well-marked horizon line, so the horizon could have been used if sights were necessary. Consider, however, the advantage of such bubble sights to a mariner off Oregon and Washington during the forest fire season, for example, when the horizon is obscured for days at a time. In addition to this, sights can be made when the horizon is invisible at night if utmost accuracy is not necessary, or possible.

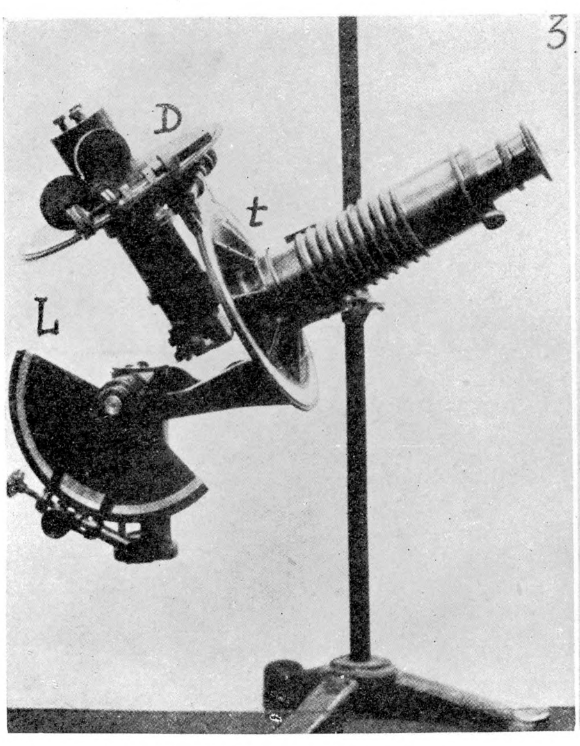
CONSTRUCTION.

The instrument contains three arcs or circles. The collimation axis of the telescope is perpendicular to, and rotates about, the axis of the declination circle. This axis is perpendicular to and rotates about the axis of the hour angle arc or "polar axis". The axis of the latitude arc is perpendicular to the polar axis and the latitude arc itself is vertical when the bubble is centred. The bubble cell is similar to that of a bubble sextant (Hereafter the vertical line passing through the bubble when it is centred will be called the *axis of the levelling device*). When the horizon is used two prisms under the bubble cell pass the rays from the horizon along this same axis, dip being allowed for by setting the height of eye on an indicator which tilts the prisms. Two portions of the horizon are used. They intersect at an angle in the field and this intersection is treated by the observer in exactly the same way as the bubble. An image of the bubble (or horizons) is superimposed upon the astronomical field by a series of reflectors (prisms)

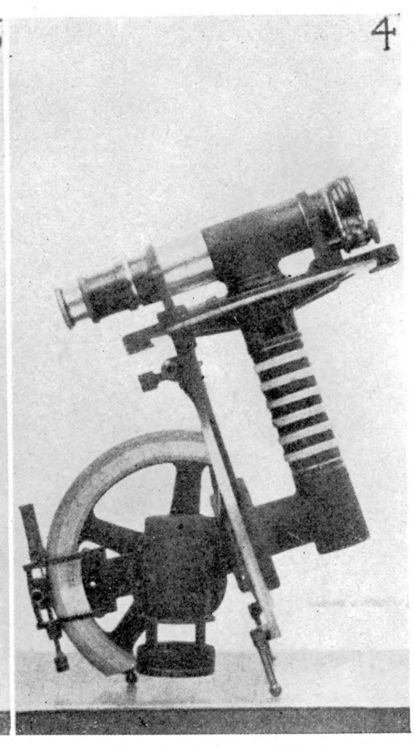
SPHERANT



First Model — Premier Modèle

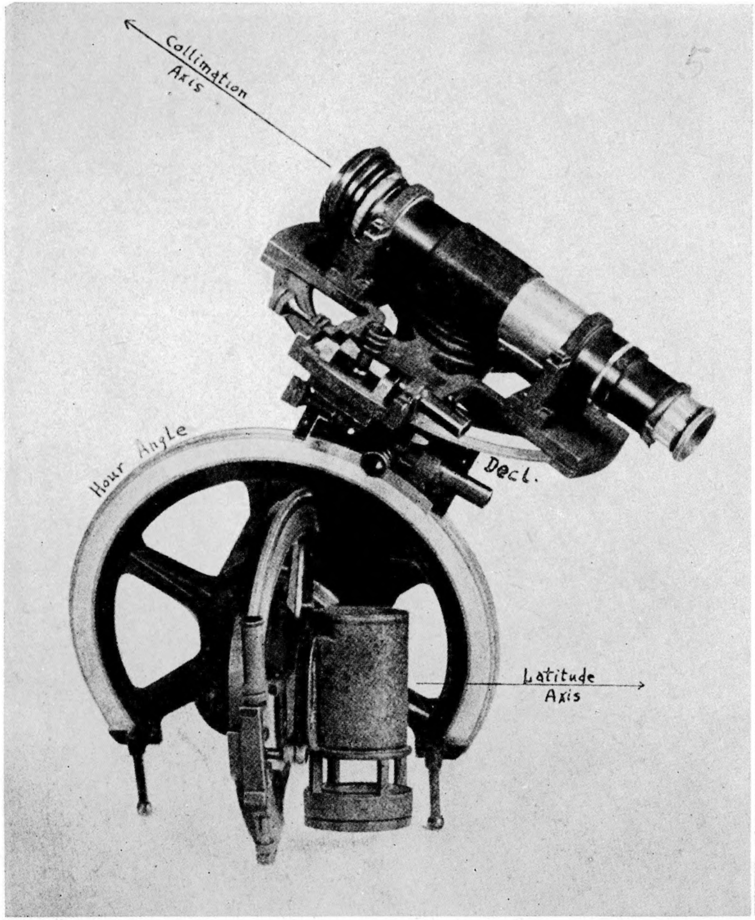


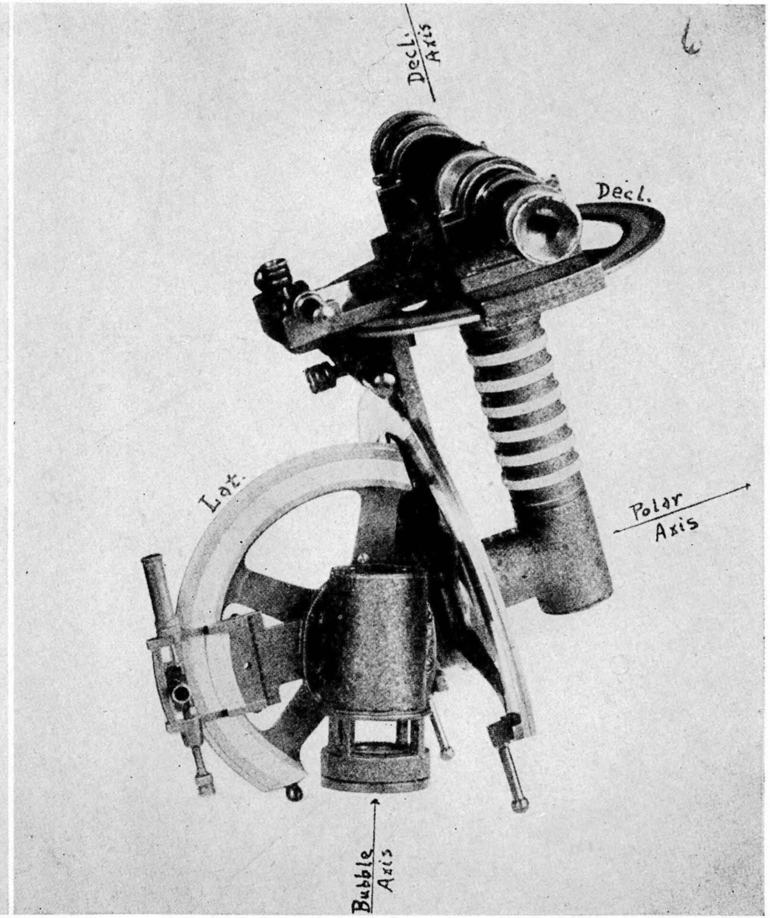
Second Model — Second Modèle



Third (final) Model
Troisième Modèle (définitif)

Two additional views of the Spherant





Deux autres vues du Spherant

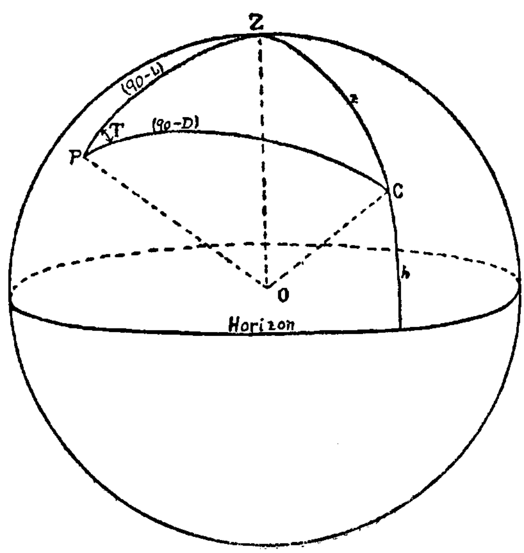
which pass the light from the bubble cell along the latitude axis, along the polar axis, then along the declination axis (the covering of which acts as a handle), and finally down the telescope tube towards the eyepiece. The latitude arc and the declination circle are graduated to one minute of arc and the hour-angle arc to four seconds of time. All three have clamps, verniers, tangent screws, etc. The declination circle reads zero in the two positions where the telescope is parallel to the hour-angle arc, and is graduated up to 90° in each direction from these points. The hour-angle arc is graduated over twelve hours (180°) and marked by two series of numbers, one reading six hours and the other eighteen hours when the declination circle is perpendicular to the latitude arc. The latitude arc reads zero when the hour-angle arc and axis of the levelling device are parallel. It is graduated up to 90°.

Use of aluminum alloys for many parts of the instrument makes possible a small total weight. The instrument illustrated weighs only two pounds and fifteen ounces which is less than the average sextant. Suitable shade glasses are placed before the telescope and in a more compact design now under construction there is room for an extension of the handle for a small dry-cell battery for illumination of the bubble at night. Adjustments are made in the factory so that all index corrections are zero and they should remain so. An accident sufficiently violent to derange the optical system would damage the instrument beyond field repair anyway. A complete set of directions for making and checking each adjustment, step by step, can be provided for the benefit of the individual who cannot refrain from investigating the interior.

In the following description the word "bubble" is used for convenience but it can be replaced by the term "intersection of horizon images" to make it apply to the use of the horizon. It is hoped that all future instruments will contain both methods of levelling when made for use at sea.

METHOD OF OPERATION.

Clamp the declination vernier at the known value of the declination of the object to be observed. Clamp the latitude and hour-angle arcs at arbitrary values and hold the axis of the levelling device vertical. This leaves the instrument free to rotate only in azimuth. Such a rotation causes the collimation axis of the telescope to sweep out an arc of a small circle parallel to the horizon. The altitude of this arc can, in general, be varied to make it pass through the object by changing the setting of either the latitude or the hour-angle arcs. The observer, looking into the telescope, in this way makes the images of the astronomical object and the bubble coincide within a ring which is marked on the bubble cell. This also makes the axis of the levelling device vertical. Some



apprehension was felt because this coincidence, although not necessarily made on the intersection of the cross wires which marks the collimation axis, must yet be made somewhere on a certain line passing through this point. This at first glance seems to leave the observer with one less degree of freedom than when observing with most sextants. The error in this reasoning is seen when it is considered that with the direct-view telescope only two motions are required to move the object about the field, whereas in the case of the sextant, where the body is brought down to the horizontal, there are three motions to be controlled, right and left, up and down, and rotation about the telescope axis. The comparison of the freedom of optical rotations in the two instruments is then closely related to the proverbial case of six of one and half a dozen of the other. Not quite so if we wish to quibble over the matter, for, in the case of the sextant, the effect of the mentioned rotation varies with the altitude, while in the case of the spherant the same amount of motion always produces the same displacement. The observer concentrates on the position of the astronomical body and gives the instrument a slight back and forth rotation about the collimation axis. This makes the bubble or intersection of the horizons move back and forth across the field. The direction of this motion is not of interest. It is merely necessary to have them pass over the astronomical object in the proper manner as they cross the field.

Consider now the relationship of the readings on the three arcs while the observer holds the instrument in this position. This study is assisted by reference to the drawing of the celestial sphere. On this drawing let Z, P, C, be the points where the axis of the levelling device, polar axis, and collimation axis respectively pierce the celestial sphere, and let L, t, D, be the respective readings of the latitude arc, hour-angle arc, and declination circle. Remembering the construction of the instrument, it is seen that the elevation of the polar axis above the horizontal equals the reading of the latitude arc. The arc PZ is then equal to $(90^\circ - L)$. The latitude arc is vertical and parallel to the polar axis, so it must lie in the plane OPZ. Since the declination circle is parallel to both the collimation and polar axes its plane cuts the celestial sphere along the arc PC. Due to the method of marking the graduations, the arc PC always equals $(90^\circ - D)$ if D is called negative when it is of opposite name to the latitude. The observer has made the angle between Z and C equal to the apparent zenith distance of the object when he placed C on the object. Let T be the angle between the arcs PZ and PC. Since the latitude arc and the declination circle are both parallel to the polar axis, the hour-angle arc measures the angle between them, its reading t being zero when they are parallel.

If the L originally set off on the latitude arc was the dead-reckoning latitude, then t is the hour-angle which would be obtained from computation by a navigator using the old time-sight formulas. He would have observed the apparent altitude, found the zenith distance z, and solved a triangle having sides z, $(90^\circ - L)$, and $(90^\circ - D)$ for angle t.

Let L_0 be the longitude resulting from combining t with the GHA at time of observation, and suppose the point whose coordinates are L and L_0 to be marked on the chart. This point is on the circle of equal altitudes, or the SUMNER circle. If another latitude had been used the same line of reasoning will show that when combined with the resulting longitude it gives another point on the circle of equal altitudes. In practice, then, there is no necessity for employing the dead-reckoning latitude if a line of position is desired. Select some even degree or half degree of latitude near it. Make the observation, subtract t from the GHA, and plot the resulting longitude at the latitude used. Change the latitude reading by 20° (30' or even 1° in some cases) and repeat. These two points are on the circle of equal altitudes. A straight line drawn through them is for all practical purposes the usual "line of position". It differs chiefly by being accurate over a longer length. The line obtained by use of the modern tables is a tangent by the MARCQ SAINT HILAIRE method, with the altitude difference laid off from a point on the full degree of latitude nearest to the dead-reckoning position. Such tangents are within a given distance from the circle of equal altitudes throughout a much shorter distance than is the secant line drawn through two points on the circle, but this is a theoretical rather than a practical difference. Those interested in the curvature of SUMNER circles are reminded of the tables of such data given in *H. O.* 203, page XVI, and in AQUINO's *Newest Sea and Air Navigation Tables*, page 115.

Two observations are not necessary as a single sight can be made and the azimuth determined by azimuth diagram, gyrocompass, etc. The second sight is, however, a matter requiring only a few seconds time. The instrument is ready except for a slight change in latitude and then a small movement in hour angle while observing. The line is on the chart immediately afterwards especially if the latitudes assumed have been those of parallels on the chart, and if the longitude scale of the chart has had the time equivalents marked beside the arc units to eliminate conversion of longitude from time to arc units. If a complete record of the work is desired in addition to the record on the chart it may have this form :

	March 30, 1930	Dec. *N* 3°47'
	37° 1/2	38°
GHA	12h36m04s	12h36m40s
t	4 27 28	4 27 28
Long	8 08 36	8 09 12

Ordinarily the two observations are made within a minute of each other — within thirty seconds if a recorder is available.

When the astronomical body is near enough to the meridian to be changing its altitude slowly, yet not near enough for the old "reduction to the meridian" methods, it is convenient (but not necessary) to set the dead reckoning hour angle or an hour angle at an assumed longitude for a short time ahead and make the observation by varying the latitude setting. This can be done leasurely as under these conditions the observation need not be made exactly at the expected time. If the D. R. hour angle has been used the result is the latitude that would have been obtained from an altitude reduced by the φ'' φ' formulas. If two widely different longitudes are assumed, a line of position is obtained. When the body is close enough to the meridian for treatment by the old "reduction of the meridian" methods it is convenient to set an approximate hour angle and observe the latitude several times before it is necessary to change the hour-angle reading.

A possibility worth mentioning is that of observing altitude or zenith distance. There are three cases where this may be desired : (1) When finding the distance of a light or other object by vertical angle; (2) When using the WEEM's *Star Altitude Curves*; (3) When the navigator so enjoys the thrill of arithmetic that he prefers to make the usual reductions. The last individual is advised to stick to the sextant as he might be tempted away from his hobby with a spherant at hand. In any event either zenith distance or altitude can be measured if desired. Set the hour-angle arc at zero. The latitude arc and declination circle are then parallel. If latitude is set at 90°, then altitude of any body under observation is found on the declination circle. If latitude arc is set at 0°, then on observing any body the declination circle gives zenith distance. Similar results can be obtained by clamping the declination circle and varying the latitude setting.

CORRECTIONS.

Little or no mention has been made yet of the usual annoyances of dip, refraction, etc. Dip does not enter, of course, in the case of the bubble. With the horizon prisms it is introduced by tilting the prisms, the indicator being graduated according to height of eye. Refraction is more troublesome but fortunately is always given by one significant figure if one minute of arc is the accuracy aimed at. Ordinary refraction-in-altitude tables cannot be used. The tables used by surveyors which give refraction in declination for use with solar attachments are suitable if accompanied by a similar table for hour angle. The surveyor's table is, however, far more eleborate than is necessary for a navigator and would require using two corrections. A simpler method is to tabulate a correction to either hour angle or declination and have this correction to one coordinate contain the refraction in that coordinate combined with a quantity which exactly offsets the effect of the refraction in the other coordinate. An observer in the afternoon, for example, desiring a line of position, makes the observation as described before, and after recording the GHA finds in the refraction table a small quantity in seconds of time which he adds to the hour-angle reading on the instrument. The same refraction is applied to the second observation. The correction can be shown on a diagram two and one-half inches square or in a table of the size of a page in the

Nautical Almanac. The moon requires two significant figures in the correction and an entire table for itself, parallax and refraction together being treated in the same manner as the refraction alone is for other bodies.

EASE OF OBSERVATION.

Probably the greatest question remaining in the mind of the reader is that of the difficulty of learning to observe with such a gadget. The optical system of the instrument can be made with the same power and field of view as any given sextant. It is then just as easy (or difficult), to observe with as the sextant if the same amount of practice is given to each. The advantages of the instrument are especially marked when teaching beginners in navigation. The beginner feels that he knows nothing in advance, so listens quietly to instructions and obeys orders. He learns the names of the arcs and how to read the verniers in a few minutes. His first sight gives a longitude or latitude correct to the nearest mile or two. A few more practice sights and he tries for a line of position. Half an hour or less after beginning the study of nautical astronomy he is looking at his first line of position on the chart. This simplicity was not realized at first. In discussions with various navigators the difficulty of teaching a beginner was sometimes mentioned, always with the idea that anything so different from a sextant would be much more difficult to learn to handle. Fortunately the truth of the matter was discovered before too many theoretical conclusions had been drawn. An enlisted man (Maury W. SHANNON, Sea 1c., U.S.S. *Aroostook*) was curious about the instrument and was allowed to attempt an observation. He had had no previous instruction in nautical astronomy but had no difficulty at all in observing longitudes according to directions. After a few of these he determined two lines of position, both of which passed one and a half miles south of the true position (chiefly because it was 2.15 p.m. on Dec. 22 and no refraction corrections were applied). He had learned the purpose of the three arcs and how to read their verniers and could observe in less time than it usually took an experienced navigator to realize that this was not a "sextant" and required a special technique.

FUTURE DEVELOPMENT.

After it has been recognized as an aviation and navigation instrument the spherant may make a further advance by combination with a gyrocompass. If a spherant were mounted on or over a gyro repeater in such a manner that the polar axis could be adjusted to the north and south line and the axis of the levelling device perpendicular to the plane of the card, it would be possible to point the telescope to an astronomocal body, in general, only by adjusting both hour angle and latitude, assuming declination to be fixed at its true value. When this adjustment has been made the latitude reading is the true latitude of the ship and the hour angle combined with the GHA is the longitude of the ship. In other words a complete fix is obtained from a single observation. To be of value it would be necessary to have the gyro repeater not only accurate to one minute of arc but its plane level with this accuracy also. This condition is by no means arrived at by any gyro as used at present, not even the remarkable gunnery gyro Mark X. The horizon-type levelling device of the spherant would, however, take care of the second requirement. Under the best conditions at present the uncertainty of the fix in the direction at right angles to the sun would be quite a few miles, just how many is somewhat a controversial matter, but the latest gyros certainly make it less than the uncertainty of the dead reckoning after a long run. The important point is, that this section of a SUMNER line or approach to a fix would be determined directly from the instrument, immediately after a single observation, and nothing has to be assumed beforehand.

SUMMARY.

Summarizing the various points: Equipped with the spherant and ***Nautical Almanac*** with a page of refractions pasted inside its cover, a navigator needs no other tables for determination of lines of position. The usual work of making several entries in a table with the resulting additions and substractions, use of parallel rulers and compass rose in laying off the azimuth, dividers for the altitude difference and parallel rulers and compass rose again for the line of position is all eliminated. This is an appreciable saving of time and worry for the surface navigator but is an enormous advantage in aircraft. It makes navigation more fool-proof and therefore safer.

Instruction in navigation is greatly simplified. A student obtains results from the start and does not pass through stages of wondering what it is all about. The instrument is seen as a model of the celestial sphere so there are no diagrams to be visualized. Under emergency conditions embryo navigators can obtain sufficient knowledge and skill in nautical astronomy for navigation purposes in a few hours.

Recently, the instrument has been further improved. The optical system has been entirely redesigned so that fields are completely visible in all positions of the instrument or the eye.

The apparatus has been submitted to a long period of test in the United States Navy which has ordered several to be constructed for its use.

The use of a second-setting navigation watch set to local time greatly facilitates the work ; the local hour being thus known to the exact second, the operation of the instrument becomes by this fact considerably simplified.