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THE AIRCRAFT BUBBLE SEXTANT, TYPE A.

By Commander R. C. Parker, U. S. Navy.

The Aircraft Bubble Sextant, Type A, was constructed from plans submitted by the Bureau of Aeronautics to fill the requirements of an instrument with which altitude of heavenly bodies could be measured without depending on a sea horizon.

While intended primarily for the use of aircraft, it will undoubtedly be found useful to surface vessels as well, since it eliminates the long period between evening and morning twilight when there may be stars in plenty but no horizon, and those other occasions so familiar to every navigator when the sun could be snatched through rifts in the fog if only there were some horizon to bring it down to.

Briefly, its principle consists in the substitution for a sea horizon of a self-contained artificial horizon, in the shape of a bubble with which the heavenly body is brought into coincidence. This principle is not to be confused with that of a theodolite, in which the instrument itself has to be adjusted to a true and steady level, nor with that of the ordinary mercury horizon in which the image of the heavenly body is made to coincide with its reflection in the liquid. In the bubble sextant the sun or star is brought down into coincidence with the bubble itself, and, within certain limits, is not dependent on holding the sextant exactly level.

The following are some of the outstanding features of its construction:

There is no graduated arc and no index bar with vernier, as in the ordinary type. The index mirror is moved by an arrangement of worm and gearing from a knurled thumb wheel, and the angle measured by its movement is recorded by a counter gear much like that on an ordinary speedometer or cyclometer.

In place of the horizon glass there is a glass bubble-cell like a round spirit-level, and the image of the bubble, by an arrangement of prisms and lenses, is projected through the index mirror and to the eye as though it were coming from an infinite distance.

In order to use the instrument in the ordinary manner on the sea horizon, as well as to check its accuracy, there is an object-glass or lens mounted in a horizontal tube beyond the bubble, which projects the image of the sea horizon or distant object through the bubble and index mirror to the eye.

The arrangement of optical parts is shown as a side view in Figure 1. B is the bubble cell, filled with Zylol except for a small bubble at the top. The top and bottom of the cell are of glass and hence the whole cell is transparent, except that the bubble itself is projected to the index mirror, M, as a dark ring with transparent center. Light is thrown through the bubble cell either from the outside through lens (L_1), and right angle prism (R), or from the small internal electric bulb (X_1). The image of the bubble, reflected in the prism, and collimated in the lens (L_2), into parallel rays as though from a distant object, is projected through the transparent index mirror (M), and to the eye (E).

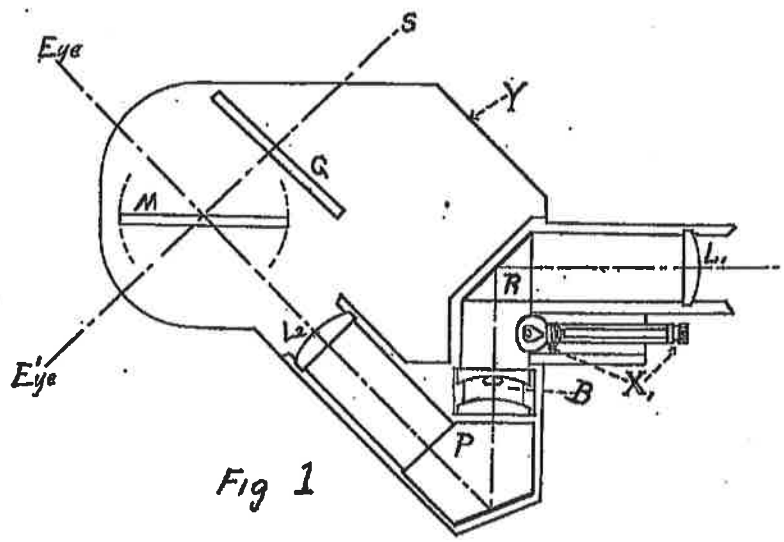

Fig 1

The index mirror (M) is turned until the reflected image from the sun or star (S) coincides with the projected image of the bubble, and the resulting angle is read off from the counter.

The two lenses, (L_1) and (L_2), together form a 1-power telescope through which the sea horizon or distant object is seen and may be used for coincidence with the sun or star in the ordinary manner; and also for adjusting the instrument, as will be explained later. The lenses are adjustable so that all parallax may be removed. A cap may be placed over the end of the telescope when it is desired to exclude terrestrial objects from the field.

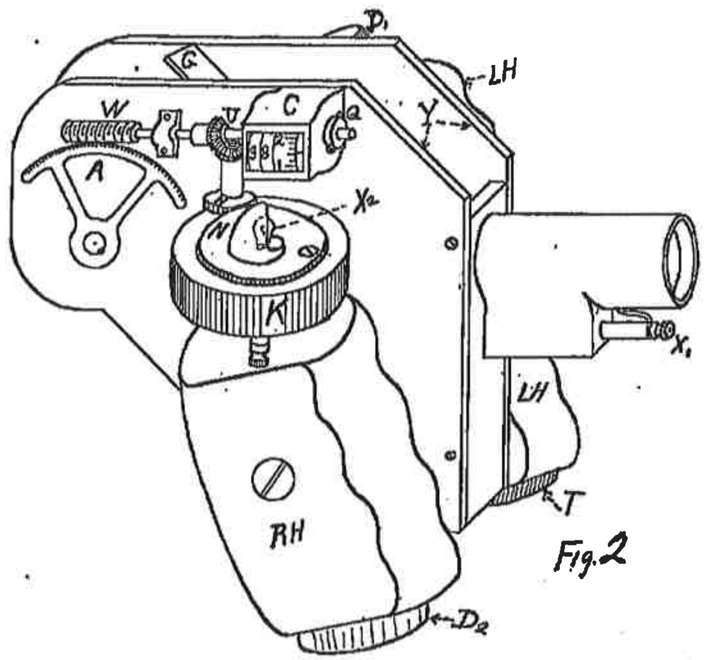

Fig. 2

Colored sun glasses, (G), may be turned into position between the index mirror and the sun.

All of these optical parts are carried between two parallel frame plates (Y), about an inch apart; the lenses, prisms and bubble cell being inside a tube, between the plates.

Outside of the frame plates (see Figure 2) is a handle or grip on each side, (RH) and (LH). At the top of the right handle is a knurled thumb wheel (K), which may be turned by the thumb and first fingers of the right hand to make the coincidence, while maintaining a grip on the handle, (RH). This thumb wheel, through two gear wheels, (N, N), a pair of bevel wheels, U, and a worm and arc (W, A), turns the index mirror (M), and also the shaft of the counter (C).

The counter and the worm are on the same shaft, so any lost motion in the gear and bevel wheels will not affect the readings of the counter and any between the worm and arc and in the counter itself is reduced to less than 1 minute.

The counter (C) consists of three graduated cylinders. The left one, numbered from 0 to 9 registers tens of degrees; the next cylinder, number from 0 to 9, registers units of degrees; and the right cylinder, numbered from 0 to 5, registers to tens of minutes by the numbers and to two minutes by graduations between the numbers. Amounts between the graduations may be readily estimated to within one-half minute. After a small amount of practice the counter may be read more easily and quickly than can the arc and vernier on a regular sextant. In Figure 2 it is shown reading 38 degrees 14 minutes 30 seconds.

The bubble sextant carries its own lighting system. From a battery of two dry cells contained inside the left handle (LH), current is supplied to the bulb (X_1) Figure 1, for illuminating the bubble, and to the shaded light (X_2) Figure 2, for illuminating the counter. At the top of the left handle, there is a rheostat knob (D_1) by which the illumination of the bubble may be adjusted for best results. At the bottom of the right handle there is a switch knob (D_2) by which the counter lamp (X_2) may be turned on or off. A cap, (T), at the bottom of the left handle, permits the removal of the dry cells.

Other features of the instrument are a watch holder on the back, to facilitate the observer in marking the time of his own sights, and a knob and pointer on the left side plate (not shown) by which the sun glasses may be set normal to the approximate altitude of the sun.

The instrument weighs about 2½ pounds, and is somewhat smaller than a regular sextant.

The design of the instrument requires that the observer hold it low, looking down into it at an angle of about 45 degrees, except when observing a star, which will be explained later. The field of the telescope with bubble in it, will be seen projected up through the transparent index mirror, the bubble as a dark ring moving about the field as the instrument wavers.

In an ordinary sextant, after the sun or star is in coincidence with the horizon, you can tip the instrument towards or away from them without causing them to separate. They will cross the field together, and an altitude can be taken in the top or bottom of the field as accurately as in the center.

Similarly with the bubble sextant, if the heavenly body or distant object is brought into coincidence with the bubble-image they will stay together while the sextant is tipped through a moderate angle, as long as the bubble moves freely. When the bubble reaches the side of its cell it will no longer function properly and observations so taken will be in error.

The exact center of the bubble is difficult to determine by eye, and hence an altitude or adjustment made by bringing an object to the center of the bubble will be liable to error. The more accurate method will be to make coincidence at top and bottom of the bubble and use the mean of them. The more coincidences taken and averaged, the greater the accuracy.

Neither the top or bottom tangent can be used alone, for the size of the bubble varies with the temperature, and hence its semi-diameter cannot be accurately estimated.

In Figure 3 the arc BB′ is the top of the bubble cell, O is its center of curvature and OB its radius. PP′ is the reflecting surface of the penta-prism, and F the point conjugate to O with reference to PP′, that is, the point such that lines drawn from any point in PP′ to both O and F will be equal and make the same angle with PP′. MM′ is the top reflecting surface of the transparent index mirror. S is any distant object or heavenly body, the rays from which are reflected upward by MM.′ By inclining MM′ these reflected rays may be made to coincide with rays passing upward from PP′.

Consider the instrument held approximately level so that the bubble, moving freely to the highest point of its cell, will rest at a position B. The downward rays from B will be reflected in the penta-prism. Draw OPB, cutting the penta reflector at P. The ray from B incident at P will be reflected up through the point F, and on through the transparent mirror at M to the eye at E.

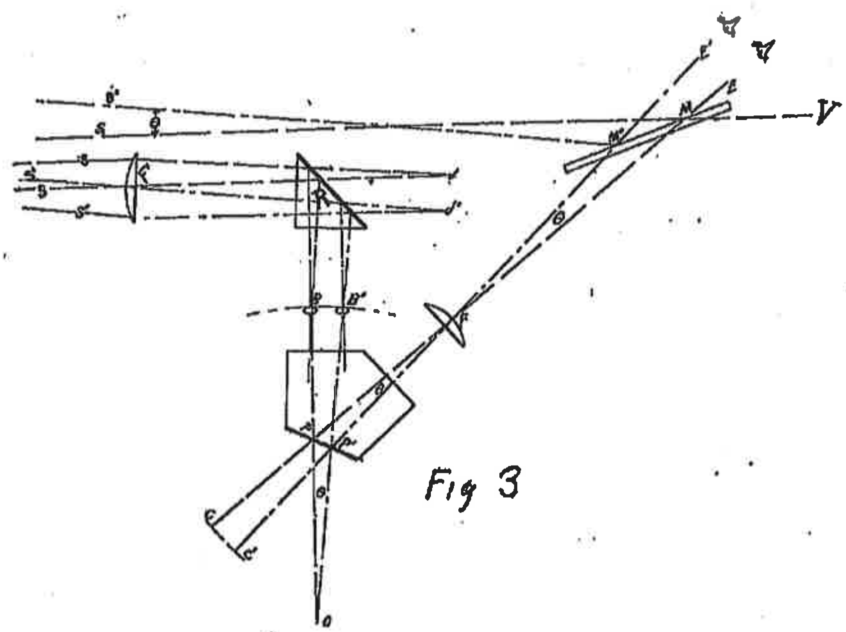

Fig 3

With the sextant held stationary, the index mirror M is now inclined until the ray SM is reflected so as to coincide with the ray BPFM along ME. Prolong SM to V, and it will be seen that MV is equivalent to a reflection of PFM as well as a continuation of SM. Considering BPFMV then as a continuous ray, we see that it obeys the law that when a ray undergoes two reflections in the same plane the angle between its first and last direction is equal to twice the angle between the reflecting surfaces.

But gravity acting on the liquid in the bubble cell makes the line BPO a true vertical between zenith and nadir. Therefore it follows that the angle between ray SM and ray BPO is the zenith distance of the body S, and is measured by half the angle between the index mirror and the penta-prism mirror. The latter is fixed with relation to the frame of the instrument; therefore the inclination of the index mirror, when measured by a suitable scale, can be made to record the true altitude of S directly.

Suppose now that the instrument be inclined through a small angle so that the bubble rests at B.′ The distant body is now at S′ relative to the instrument, but the angle between S′M′ and B′P′O has not changed from that between SM and BPO, and the same position of the index mirror still measures the altitude of A. Or putting it in plain language, the bubble moves through the field the same angular distance that the instrument is inclined, and hence its coincidence with the heavenly body is not affected by movement from B to B′, as the sextant is inclined.

In the foregoing demonstration only the single ray passing from B through F has been considered, for the sake of clearness. In actual fact an infinite number of rays radiate from any illuminated point. If the point be distant like S then the rays are received at the eye or the instrument sensibly parallel to each other. If the point be near like B, the rays are divergent but may be collected into parallelism by a suitable lens.

Referring to Figure 4 such a lens is placed at F, its focal center being conjugate to the point O, and its focal length being equal to the radius of the bubble cell and to FPB. It will be seen that all the downward rays from the bubble, B, are reflected by the penta-prism to the lense and emerge therefrom parallel to each other and to the central ray drawn through the focal center of the lens at F, as though B were at an infinite distance. In Figure 4 the heavenly body, S, is shown at an altitude of 45 degrees, so the mirror, M, must be inclined to

22½ degrees with reflector P to make coincidence between the bubble rays and those from S. Movement of the eye to different positions of E does not affect the coincidence.

Up to this point we have neglected the prism R and lens F′, located above and to the front, which play no part in the ordinary use of the sextant with the bubble, but function in the adjustment of the instrument and in using it on the sea horizon like the ordinary nautical type.

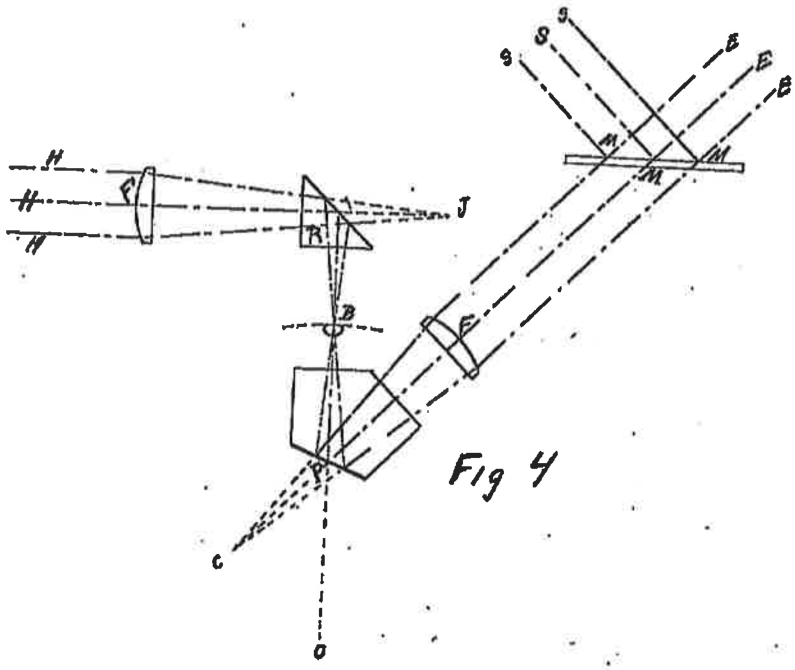

Fig 4

The lens F′ is so located with reference to the right-angled prism R and the bubble-cell that the distance F′RB equals its focal length F′RJ, and the bubble is therefore in the focal plane of both lenses.

Referring again to Figure 3, rays from S incident on the lens F′ comes to an imaginary focus at J and are actually reflected down by the prism R to the bubble-cell, which is transparent. By proper mounting of the prism, R, these rays may be made to focus at B. This adjustment is permanent and

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thereafter if the instrument be tilted through θ, the rays from S′ follow the bubble from B to B′, with the result that an image of S may be seen in the field of the telescope, coincident with the bubble image.

The telescopic image of S is distinct from the image of S reflected in the index mirror M, but may be made to coincide with it by inclination of the index mirror, just as is done when finding the index correction of a nautical sextant. For simplicity we shall call the former the projected image of S, and the latter the reflected image.

To use this instrument as a nautical sextant, the sea horizon is kept in the telescopic field and the image of the sun or star, reflected in the index mirror, is made to coincide with the image of the horizon in the telescope, disregarding the bubble entirely.

The adjustment of this bubble sextant for either type of use is the same in general principle as that of an ordinary sextant; that is, a known angle, preferably zero, is measured, and the scale is either adjusted to read zero on this angle, or the difference from zero is carried as a constant index correction.

In Figure 8 assume S or S′ to be in the true horizon or actually level with the instrument, and that by turning the index mirror its reflected image in M and M′ has been brought to coincide with the bubble image.

The scale should now read zero degrees, zero minutes. If it does not, we may carry the difference from zero as an index correction, or we may eliminate it by resetting the scale to zero for this same position of the index mirror.

Similarly we may make coincidence between the image of S reflected in M and the projected image of S seen *through* M. If the index correction by both methods is the same, then resetting the scale to zero will eliminate it for both of them. If it is not the same then it means that the projected image of S does not exactly coincide with the bubble image, and a resultant error is bound to be left in one of them.

The following procedure for adjustment is recommended: To establish a true horizon range, set up a stand for the sextant at some convenient point ashore; then with a theodolite or surveyor's level at the same height as the sextant sweep the skyline until some roof, chimney or other distinct point or line is discovered at exactly the same level and preferably not less than two miles away. It may be necessary to vary the height of the sextant stand to get this level accurate to less than a minute of arc. Call the point or line selected the true horizon point, H.

With its scale set at zero, set the sextant on the stand and swing it in azimuth until the two inverted images of the true horizon point are together in the center of the field laterally. Incline the sextant until the bubble is seen in the center of the field as nearly as can be determined by eye, and clamp or block it in that position.

Now disregarding the projected image, turn the index mirror by the thumb knob, K, until the reflected image of the true horizon point, H, is in the center of the bubble image. Since the center is difficult to estimate with accuracy, it is preferable to bring the true horizon point alternately into coincidence with top and bottom edges of the bubble for several readings of the counter which should be recorded. The mean of these readings will equal the reading for the center of the bubble, and should be zero, but may differ slightly; a mean reading of 99 degrees 58 minutes, for example, would be an index correction of plus 2 minutes on the bubble. (The scale is graduated from zero to 100.)

Now bring the same reflected image of the true horizon point into coincidence with its own projected image several times, and take the mean scale reading as before. If it came to 99 degrees 58 minutes also, it would show that the true horizon image centered accurately with the bubble image, and that the instrument as a whole read 2 minutes low, whether used with the bubble or with a visible true horizon. It would then only be necessary to shift the counter scale to read 2 minutes higher, or zero for the mean of several observations, or to carry the constant index correction of plus 2 minutes.

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If the mean of the coincidences taken with the bubble did *not* agree with those taken on the projected true horizon point, it would indicate that the latter was not being projected through the exact center of the bubble. This can only be corrected by shifting the right angle prism (R), and it is not recommended that this be attempted except by an experienced optical mechanic.

If this error is found, it does not prohibit the use of the instrument in either way, for one may either carry in mind the two different index corrections, or the counter may be adjusted so as to take out the index correction on one, and leave it on the other. Thus, if the mean of the observations using the bubble were 99 degrees 58 minutes and the mean using the projected image of the true horizon point were 00 degrees 1 minute, we could leave them as index corrections of plus 2 minutes and minus 1 minute, respectively, or we could take it out of the former and have minus 3 minutes left on the latter.

The counter scale may be adjusted by slacking up the set-screws in the clamp collar, Q, on the end of the counter shaft, and turning the collar with the fingers until it reads zero. Be careful not to move the thumb wheel or counter shaft while doing so. In the zero position one set screw may be inside out of reach; turn this outside and slack it first before slacking the other, and the same when tightening up again.

Suppose the mean of several coincidences between the true horizon point and the bubble is 0 degree 03 minute, or an I. C. of -3 minutes. Turn the thumb wheel (and index mirror) until the scale reads 0 degree 03 minute, slack off the set screws carefully and turn the counter until it reads 0 degree 00 minute then tighten the set screws and recheck.

The index error found by coincidences between the reflected and projected images of H may be taken out in the same way, though it is presumably better to take it out of the bubble coincidence and leave the residual error, if any, in the use of the instrument as an ordinary nautical sextant.

The design of the instrument—light transmission shafting, small worm and gearing, and an index mirror supported only by light trunnion bearings—makes this instrument considerably more subject to change in the index correction than the ordinary nautical sextant, which has its index mirror mounted solidly to the index bar, and which reads directly from a graduated arc instead of through a gear-driven counter. It is, therefore, advisable to check the index correction before and after all observations.

But it is, of course, impossible to check the correction on the bubble without the aid of a true horizon point or distant body of known true altitude which will be impossible from a plane; whereas the correction for coincidence between reflected and projected images of distant objects may be taken at any time, using the sea horizon, heavenly body, or distant object.

Now if there is no difference between the two I. C.'s, or if the difference be known and assumed constant, then one I. C. can readily be found from the other. These assumptions are likely to be correct, for any slight displacement of the index mirror or counter gear will throw an equal error into both methods of using the sextant, and the two I. C.'s will not differ unless the prisms be displaced, which is not so likely to occur provided the instrument receives reasonable care.

The following method is recommended for handling the corrections: Using a true horizon point H, make coincidence between it and the bubble and get the index correction, calling it "B." Then make coincidences between the reflected and projected images of H and get the other index correction, calling it "D."

Consider this "B" − "D" as a constant to be recorded. Then subsequently, when "D" is observed but "B" cannot be, we can nevertheless find it by the simple formula "(B − D) plus D equals B," just as in taking the time of sights we add (C − W) to W to get C again. If no change is found in D, we may assume the same of B, while if D has changed B will have presumably changed an equal amount.

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There seems no reason why a true horizon range could not be found or constructed at any Naval Station. All that is necessary is a stand for the sextant (possibly under cover), blocks or clamps for holding it in position, and a clearly defined point about two miles away and on the same true level as the sextant to within a minute of arc. A point made in the shape of a cross of timber would be excellent.

The following methods are suggested for testing on board ship; which, while rough, may at least be used as a check on previous adjustment:

(*a*) Using another ship for true horizon point. All that is necessary is that she be far enough away, that you can determine the height of some line or point aboard of her and set up sextant at the same height above waterline on your own vessel, and that there be not enough motion to change these heights. An error in relative height of one foot will cause an error in checking of only about 1 minute in a thousand yards, and less in proportion at greater distances.

(*b*) Using the sea horizon. Find the exact "dip" of the height at which you are working. Bring the reflected image of the sea horizon to coincide with the bubble image for several observations at top and bottom, and take the mean of them. The result, which will be below zero, or "Off the arc," should be the same as the "dip," or the difference between them is the index correction. Compare this with the index correction obtained by direct coincidence between the reflected and projected images of the horizon.

(*c*) By observations on a heavenly body. Select a certain watch time for the test ahead of time, reduce this to G.M.T., and calculate the altitude for this time just as is done in an ordinary line-of-position sight, correcting it for Semi-Diameter and P & R with reversed signs. Then take observations with the bubble sextant, starting a few minutes before the selected watch time, and getting as many as possible, recording the times of each. Plot a fair curve of times and altitudes, which will give a more accurate check than a single observation taken at the exact instant selected. Any error in the elements used to compute the true altitude will, of course, affect the accuracy of the comparison.

(*d*) Comparison with an ordinary sextant. Take simultaneous altitudes by bubble sextant and by a good sextant of ordinary type. Correct latter for dip and any I. C. it may have. Plot fair curves of time and altitude for each and compare them.

Methods (C) and (D) would be less practicable for making an actual adjustment, but would be interesting as showing the performance of the instrument in measuring angles other than zero.

There seems no way of checking the index correction on the bubble from a plane in flight, for the "dip" would presumably be too inaccurately known to use the sea horizon, and any form of true horizon is out of the question. The index correction by direct coincidence may be taken on the sea horizon, however, and if it has not changed, it is safe to assume that the index correction on the bubble has not changed either, or if it has changed, they have both presumably changed alike, since the change is more likely due to the mirror or counter than to the prisms or lenses.

Some other points to be noted in connection with this instrument are as follows:

There may be a certain amount of lost motion in the worm and counter gear, and this should be ascertained by a series of observations on the same point, moving first from high to low on the scale and then from low to high, and comparing the two averages. To eliminate this error it is desirable to make all adjustments and observations moving in the same direction.

In taking observations of stars or planets the instrument is held *above* the eye instead of below. The bubble image is then seen reflected from the lower side of the index mirror instead of through it, and the star is seen *through* it instead of reflected. No change in principle is involved. It is so used because the star, being a difficult target to locate and hold at best, can be seen better directly through the mirror than when reflected from it.

Considerably more practice is required with this instrument than with an ordinary nautical sextant, as it has to be held fairly steady with reference to three different planes, or axes.

Tilting it in the plane towards or away from the target causes the images of bubble and target to cross the field vertically together until the bubble touches the sides of its cell, after which it no longer functions.

Swinging it in azimuth does not move the bubble, but causes the inverted image of an object projected through the telescope to cross the field in the same direction, while the inverted image of the object reflected in the index mirror crosses the field in the opposite direction.

Tilting it sidewise causes the bubble to cross the field laterally, as well as tilting the image of any body reflected or projected. This throws in the same error as occurs in the nautical sextant when the sun, instead of being brought straight down to the nearest point of the horizon, is brought down obliquely.

The best way to observe is (1) Set the scale for the approximate altitude of the body to be observed, (2) hold sextant so that bubble appears approximately in center of field, (3) swing it in azimuth until sun or star is vertically in line with the bubble, and (4) turn thumb knob to make coincidence.

On first looking into the field and noting the images of the bubble and distant body, there appears to be a large amount of parallax between them. On closer examination it will be seen that the parallax is in the bright center, instead of the bubble as a whole, due to the fact that the bubble itself becomes a sort of irregular lens. All estimates of the center of the bubble should, therefore, be made with reference to the outer circumference of the bubble, instead of the inner part.

There is some true parallax at the sides of the field, so that observations should be taken at the center as far as possible.

The great difficulty in taking accurate observations is due to the vibration or swaying of the bubble due to unsteadiness of the hand, as distinguished from its natural movement under the force of gravity and inclination of the instrument. When used from a plane or from a ship in a seaway, it will probably be best to bring the sun or star to the center of the bubble, taking several observations as rapidly as possible and using the mean of them.

For adjustment, when the instrument can be held steady, it will be more accurate to take the mean of coincidences with the top and bottom of it, as before stated.

DISCUSSION.

Lieutenant M. F. Schoeffel, U. S. Navy.

The aircraft sextant is necessarily different from the Marine sextant, for, when the plane is at any considerable altitude the horizon is generally not visible. Even in case the horizon can be seen the altimeter does not indicate the altitude with sufficient reliability to determine the height of eye correction accurately.

For these reasons the aircraft sextant must embody its own horizon within itself. Three lines of approach to this desideratum have been attempted:

(*a*) Gyroscopic horizons.
(*b*) Pendulous horizons.
(*c*) Bubble horizons.

The gyroscopic sextants have been either mechanically or operationally complicated. The pendulous sextants have found little favor. Development has been mainly concentrated upon bubble sextants, because of their simplicity.

All three of these types of sextants suffer from the disadvantage that the horizon element is acted upon, not by the gravitational acceleration alone, but by the resultant of the gravitational acceleration and whatever other accelerations may exist upon the airplane at the instant of taking the sight. No device suitable for incorporation in an aircraft sextant is known at the present time which will react to the gravitational acceleration alone, ignoring the other accelerations.

Since these accelerational errors, which frequently are of the order of 2 degrees, or 120 miles, are inherent in the design of the sextant, it follows that success in its use is very largely dependent upon the skill of the pilot in flying the plane steadily. The best pilot cannot fly with even approximate steadiness in bumpy air, and even in smooth air the steadiness of flight is by no means absolute.

Experience has shown that the best results can only be obtained by taking a number of sights (six or seven) as rapidly as possible and averaging the readings. In still air, an error of seven or eight miles may be expected when this method is used, and in bumpy air an error of twenty miles is good work.

Since the major source of error in aircraft sextants, as built up to the present time, is due to the inherent defect of the physical principle involved, the designers have concentrated largely upon attempting to develop an instrument which is handy to use. Handiness is considered to be essential in aircraft sextants because of the difficulties imposed by cramped space, plane vibration, and the fatigue incidental to flying.

The Type A sextant described by Commander Parker is considered to be a good example of a modern instrument designed with these difficulties in view. It does not overcome the fundamental accelerational error.

As yet no satisfactory solution of the problem of the accelerational error has been devised and the aircraft sextant remains an inaccurate instrument when used in the air.