CHAPTER VIII.

INSTRUMENTS EMPLOYED IN NAUTICAL ASTRONOMY.

THE SEXTANT.

239. The *sextant* is an instrument for measuring the angle between two objects by bringing into coincidence at the eye of the observer rays of light received directly from the one and by reflection from the other, the measure being afforded by the inclination of the reflecting surfaces. By reason of its small dimensions, its accuracy, and, above all, the fact that it does not require a permanent or a stable mounting but is available for use under the conditions existing on shipboard, it is a most important instrument for the purposes of the navigator. While the sextant is not capable of the same degree of accuracy as fixed instruments, its measurements are sufficiently exact for navigation.

240. Description.—A usual form of the sextant is represented in figure 32. The frame is of brass or some similar alloy. The graduated arc, AA, generally of silver, is marked in appropriate divisions; in the finer sextants, each division represents 10′, and the vernier affords a means of reading to 10″. A wooden handle, H, is provided for holding the instrument. The *index mirror*, M, and *horizon mirror*, *m*, are of plate glass, and are silvered, though the upper half of the horizon glass is left plain to allow direct rays to pass through unobstructed. To give greater distinctness to the images, a small *telescope*, E, is placed in the line of sight; it is supported in a ring, K, which can be moved by a screw in a direction at right angles to the plane of the sextant, thus shifting the axis of the telescope, and therefore the plane of reflection; this plane, however, always remains parallel to that of the instrument, the motion of the telescope being intended merely to regulate the relative brightness of the direct and reflected image. In the ring, K, are small screws for the purpose of adjusting the telescope by making its axis parallel with the plane of the sextant. The vernier is carried on the end of an index bar pivoted beneath the index mirror, M, and thus travels along the graduated scale, affording a measure for any change of inclination of the index mirror; a reading glass, R, attached to the index bar and turning upon a pivot, S, facilitates the reading of vernier and scale. The index mirror, M, is attached to the head of the index bar, with its surface perpendicular to the plane of the instrument; an adjusting screw is fitted at the back to permit of adjustment to the perpendicular plane. The fixed glass *m*, half silvered and half plain, is called the *horizon glass*, as it is through this that the

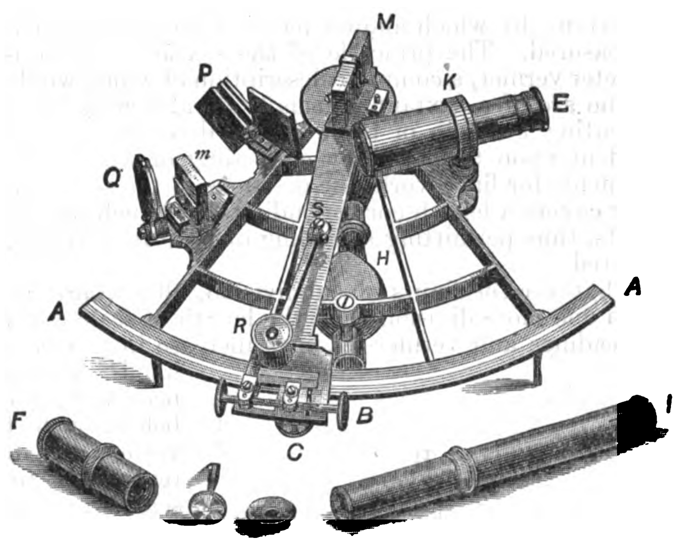

Fig. 32.

horizon is observed in measuring altitudes of celestial bodies; it is provided with screws, by which its perpendicularity to the plane of the instrument may be adjusted. At P and Q are colored glasses of different shades, which may be used separately or in combination to protect the eye from the intense light of the sun. In order to observe with accuracy and make the images come precisely in contact, a *tangent screw*, B, is fixed to the index, by means of which the latter may be moved with greater precision than by hand; but this screw does not act until the index is fixed by the screw C at the back of the sextant; when the index is to be moved any considerable amount, the screw C is loosened; when it is brought near to its required position the screw must be tightened, and the index may then be moved gradually by the tangent screw.

Besides the telescope, E, the instrument is usually provided with an inverting telescope, I, and a tube without glasses, F; also, with a cap carrying colored glasses, which may be put on the eye end of the telescope, thus dispensing with the necessity for the use of the colored shades, P and Q, and eliminating any possible errors which might arise from nonparallelism of their surfaces.

The latest type of sextant furnished to the United States Navy is fitted with an endless tangent screw which carries a micrometer drum from which the seconds of arc are read. By pressure of the thumb the tangent screw is released and the index bar may be moved to any position on the arc by hand, where the tangent screw is again thrown into gear by releasing the pressure of the thumb. The endless tangent screw is accomplished by cutting the edge of the arc with the worm teeth into which the tangent screw gears. At night the reading of this sextant is facilitated by a small electric light carried on it and supplied by a battery contained in the handle.

241. The *vernier* is an attachment for facilitating the exact reading of the scale of a sextant, by which aliquot parts of the smallest divisions of the graduated scale are measured. The principle of the sextant vernier is identical with that of the barometer vernier, a complete description of which will be found in article 52, Chapter II. The arc of a sextant is usually divided into 120 or more parts, each division representing 1°; each of these degree divisions is further subdivided to an extent dependent upon the accuracy of reading of which the sextant is capable. In the instruments for finer work, the divisions of the scale correspond to 10′ each, and the vernier covers a length corresponding to 59 such divisions, which is subdivided into 60 parts, thus permitting a reading of 10″; all sextants, however, are not so closely graduated.

Whatever the limits of subdivision, all sextants are fitted with verniers which contain one more division than the length of scale covered, and in which, therefore, scale-readings and vernier-readings increase in the same direction—toward the left hand. To read any sextant, it is merely necessary to observe the scale division next below, or to the right of, the zero of the vernier, and to add thereto the angle corresponding to that division of the vernier scale which is most nearly in exact coincidence with a division of the instrument scale.

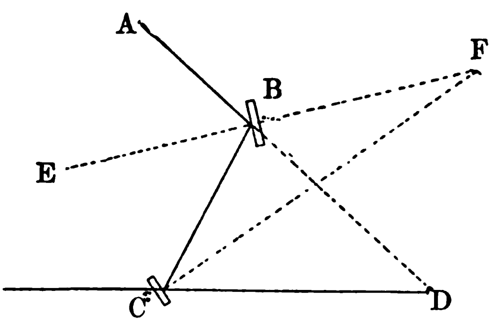

FIG. 33.

242. OPTICAL PRINCIPLE.—When a ray of light is reflected from a plane surface, the angle of incidence is equal to the angle of reflection. From this it may be proved that when a ray of light undergoes two reflections in the same plane the angle between its first and its last direction is equal to twice the inclination of the reflecting surfaces. Upon this fact the construction of the sextant is based.

In figure 33, let B and C represent respectively the index mirror and horizon mirror of a sextant; draw EF perpendicular to B, and CF perpendicular to C; then the angle CFB represents the inclination of the two mirrors. Suppose a ray to proceed from A and undergo reflection at B and at C, its last direction being CD; then ADC is the angle between its first and last directions, and we desire to prove that $ADC = 2\,CFB$.

From the equality of the angles of incidence and reflection:

$$ABE = EBC, \text{ and } ABC = 2\ EBC;$$
$$BCF = FCD, \text{ and } BCD = 2\ BCF.$$

From Geometry:

$$ADC = ABC - BCD = 2\ (EBC - BCF) = 2\ CFB,$$

which is the relation that was to be proved.

243. In the sextant, since the index mirror is immovably attached to the index arm, which also carries the vernier, it follows that no change can occur in the inclination between the index mirror and the horizon mirror, excepting such as is registered by the travel of the vernier upon the scale.

If, when the index mirror is so placed that it is nearly parallel with the horizon mirror, an observer direct the telescope toward some well-defined object, there will be seen in the field of view two separate images of the object; and if the inclination of the index mirror be slightly changed by moving the index bar, it will be seen that while one of the images remains fixed the other moves. The fixed image is the direct one seen through the unsilvered part of the horizon glass, while the movable image is due to rays reflected by the index and horizon mirrors. When the two images coincide these mirrors must be parallel (assuming that the object is sufficiently distant to disregard the space which separates the mirrors; in this position of the index mirror the vernier indicates the true zero of the scale. If, however, instead of observing a single object, the instrument is so placed that the direct ray from one object appears in coincidence with the reflected ray of a second object, then the true angle between the objects will be twice the angle of inclination between the mirrors, or twice the angle measured by the vernier from the true zero of the scale. To avoid the necessity of doubling the angle on the scale, the latter is so marked that each half degree appears as a whole degree, whence its indications give the whole angle directly.

244. Adjustments of the Sextant.—The theory of the sextant requires that, for accurate indications, the following conditions be fulfilled:

(*a*) The two surfaces of each mirror and shade glass must be parallel planes.

(*b*) The graduated arc or limb must be a plane, and its graduations, as well as those of the vernier, must be exact.

(*c*) The axis must be at the center of the limb, and perpendicular to the plane thereof.

(*d*) The index and horizon glasses must be perpendicular, and the line of sight parallel to the plane of the limb.

Of these, only the last named ordinarily require the attention of the navigator who is to make use of the sextant; the others, which may be called the *permanent adjustments*, should be made before the instrument leaves the hands of the maker, and with careful use will never be deranged.

245. The *Adjustment of the Index Mirror* consists in making the reflecting surface of this mirror truly perpendicular to the plane of the sextant. In order to test this, set the index near the middle of the arc, then, placing the eye very nearly in the plane of the sextant and close to the index mirror, observe whether the direct image of the arc and its image reflected from the mirror appear to form one continuous arc; if so, the glass is perpendicular to the plane of the sextant; if the reflected image appears to droop from the arc seen directly, the glass leans backward; if it seems to rise, the glass leans forward. The adjustment is made by the screws at the back of the mirror.

246. The *Adjustment of the Horizon Mirror* consists in making the reflecting surface of this mirror perpendicular to the plane of the sextant. The index mirror having been adjusted, if, in revolving it by means of the index arm, there is found one position in which it is parallel to the horizon glass, then the latter must also be perpendicular to the plane of the sextant. In order to test this, put in the telescope and direct it toward a star; move the index until the reflected image appears to pass the direct image; if one passes directly over the other the mirrors must be parallel·

if one passes on either side of the other the horizon glass needs adjustment, which is accomplished by means of the screws attached.

The sea horizon may also be used for making this adjustment. Hold the sextant vertically and bring the direct and the reflected images of the horizon line into coincidence; then incline the sextant until its plane makes but a small angle with the horizon; if the images still coincide the glasses are parallel; if not, the horizon glass needs adjustment.

247. The *Adjustment of the Telescope* must be so made that, in measuring angular distances, the line of sight, or axis of the telescope, shall be parallel to the plane of the instrument, as a deviation in that respect, in measuring large angles, will occasion a considerable error. To avoid such error, a telescope is employed in which are placed two wires, parallel to each other and equidistant from the center of the telescope; by means of these wires the adjustment may be made. Screw on the telescope, and turn the tube containing the eyeglass till the wires are parallel to the plane of the instrument; then select two clearly defined objects whose angular distance must be not less than 90°, because an error is more easily discovered when the angle is great; bring the reflected image of one object into exact coincidence with the direct image of the other at the inner wire; then, by altering slightly the position of the instrument, make the objects appear on the other wire; if the contact still remains perfect, the axis of the telescope is in its right situation; but if the two objects appear to separate or lap over at the outer wire the telescope is not parallel, and it must be rectified by turning one of the two screws of the ring into which the telescope is screwed, having previously unturned the other screw; by repeating this operation a few times the contact will be precisely the same at both wires, and the axis of the telescope will be parallel to the plane of the instrument.

Another method of making this adjustment is to place the sextant upon a table in a horizontal position, look along the plane of the limb, and make a mark upon a wall, or other vertical surface, at a distance of about 20 feet; draw another mark above the first at a distance equal to the height of the axis of the telescope above the plane of the limb; then so adjust the telescope that the upper mark, as viewed through the telescope, falls midway between the wires. Some sextants are accompanied by small sights whose height is exactly equal to the distance between the telescope and the plane of the limb; by the use of these, the necessity for employing the second mark is avoided and the adjustment can be very accurately made.

248. The errors which arise from defects in what have been denominated the *permanent adjustments* of the sextant may be divided into three classes, namely: Errors due to faulty centering of the axis, called *eccentricity;* errors of graduation; and errors arising from lack of parallelism of surfaces in index mirror and in shade glasses.

The errors due to eccentricity and faulty graduation are constant for the same angle, and should be determined once for all at some place where proper facilities for doing the work are at hand; these errors can only be ascertained by measuring known angles with the sextant. If angles of 10°, 20°, 30°, 40°, etc., are first laid off with a theodolite or similar instrument and then measured by the sextant, a table of errors of the sextant due to eccentricity and faulty graduation may be made, and the error at any intermediate angle found by interpolation; this table will include the error of graduation of the theodolite and also the error due to inaccurate reading of the sextant, but such errors are small. Another method for determining the combined errors of eccentricity and graduation is by measuring the angular distance between stars and comparing the observed and the computed arc between them, but this process is liable to inaccuracies by reason of the uncertainty of allowances for atmospheric refraction.

Errors of graduation, when large, may be detected by "stepping off" distances on the graduated arc with the vernier; place the zero of the vernier in exact coincidence with a division of the arc, and observe whether the final division of the vernier also coincides with a division of the arc; this should be tried at numerous positions of the graduated limb, and the agreement ought to be perfect in every case.

The error due to a prismatic index mirror may be found by measuring a certain unchangeable angle, then taking out the glass and turning the upper edge down, and measuring the angle again; half the difference of these two measures will be the error at that angle due to the mirror. From a number of measures of angles in this manner, a table similar to the one for eccentricity and faulty graduation can be made; or the two tables may be combined. When possible to avoid it, however, no sextant should be used in which there is an index mirror which produces a greater error than that due to the probable error of reading the scale. Mirrors having a greater angle than 2″ between their faces are rejected for use in the United States Navy. Index mirrors may be roughly tested by noting if there is an elongated image of a well-defined point at large angles.

Since the error due to a prismatic horizon mirror is included in the index correction (art. 249), and consequently applied alike to all angles, it may be neglected.

Errors due to prismatic shade glasses can be determined by measuring angles with and without the shade glasses and noting the difference. They may also be determined, where the glasses are so arranged that they can be turned through an angle of 180°, by measuring the angle first with the glass in its usual position and then reversed, and taking the mean of the two as the true measure.

249. Index Error.—The *Index Error* of a sextant is the error of its indications due to the fact that when the index and horizon mirrors are parallel the zero of the vernier does not coincide with the zero of the scale. Having made the adjustments of the index and horizon mirrors and of the telescope, as previously described, it is necessary to find that point of the arc at which the zero of the vernier falls when the two mirrors are parallel, for all angles measured by the sextant are reckoned from that point. If this point is to the left of the zero of the limb, all readings will be too great; if to the right of the zero, all readings will be too small.

If desirable that the reading should be zero when the mirrors are parallel, place the zero of the vernier on zero of the arc; then, by means of the adjusting screws of the horizon glass, move that glass until the direct and reflected images of the same object coincide, after which the perpendicularity of the horizon glass should again be verified, as it may have been deranged by the operation. This adjustment is not essential, since the correction may readily be determined and applied to the reading. In certain sextant work, however, such as surveying, it will be very convenient to be relieved of the necessity of correcting each angle observed. The sextant should never be relied upon for maintaining a constant index correction, and the error should be ascertained frequently. It is a good practice to verify the correction each time a sight is taken.

250. The *Index Correction* may be found (*a*) by a star, (*b*) by the sea horizon, and (*c*) by the sun.

(*a*) Bring the direct and reflected images of a star into coincidence, and read off the arc. The index correction is numerically equal to this reading, and is positive or negative according as the reading is on the right or left of the zero.

(*b*) The same method may be employed, substituting for a star the sea horizon, though this will be found somewhat less accurate.

(*c*) Measure the apparent diameter of the sun by first bringing the upper limb of the reflected image to touch the lower limb of the direct image, and then bringing the lower limb of the reflected image to touch the upper limb of the direct image.

Denote the readings in the two cases by r and r'; then, if S = apparent diameter of the sun, and R = the reading of the sextant when the two images are in coincidence, we have:

$$r = R + S,$$
$$r' = R - S,$$
$$R = \tfrac{1}{2}(r + r').$$

As R represents the *error*, the *correction* will be −R. Hence the rule: Mark the readings when *on* the arc with the *negative* sign; when *off*, with the *positive* sign; then the index correction is one-half the algebraic sum of the two readings.

Example: The sun's diameter is measured for index correction as follows: On the arc, 31′ 20″; off the arc, 33′ 10″. Required the correction.

On the arc,	−31′	20″
Off the arc,	+33	10
2)	+ 1	50
I. C.,	+ 0	55

251. From the equations previously given, it is seen that:

$$S=\frac{1}{2}(r-r');$$

hence, if the observations are correct, it will be found that the sun's semidiameter, as given in the Nautical Almanac for the day of observation, is equal to one-fourth the algebraic difference of the readings. If required to obtain the index correction with great precision, several observations should be taken and the mean used, the accuracy being verified by comparing the tabulated with the observed semidiameter. If the sun is low, the horizontal semidiameter should be observed, to prevent the error that may arise from unequal refraction.

252. Use of the Sextant.—To measure the angle between any two visible objects, point the telescope toward the lower one, if one is above the other, or toward the left-hand one, if they are in nearly the same horizontal plane. Keep this object in direct view through the unsilvered part of the horizon glass, and move the index arm until the image of the other object is seen by a double reflection from the index mirror and the silvered portion of the horizon glass. Having gotten the direct image of one object into nearly exact contact with the reflected image of the other, clamp the index arm and, by means of the tangent screw, complete the adjustment so that the contact may be perfect; then read the limb.

In measuring the altitude of a celestial body above the sea horizon, it is necessary that the angle shall be measured to that point of the horizon which lies vertically beneath the object. To determine this point, the observer should move the instrument slightly to the right and left of the vertical, swinging it about the line of sight as an axis, taking care to keep the object in the middle of the field of view. The object will appear to describe the arc of a circle, and the lowest point of this arc marks the true vertical.

The shade glasses should be employed as may be necessary to protect the eye when observing objects of dazzling brightness, such as the sun, or the horizon when the sun is reflected from it at a low altitude. Care must be taken that the images are not too bright or the eye will be so affected as to interfere with the accuracy of the observations.

253. Choice of Sextants.—The choice of a sextant should be governed by the kind of work which is required to be done. In rough work, such as surveying, where angles need only be measured to the nearest 30″ the radius may be as small as 6 inches, which will permit easy reading, and the instrument can be correspondingly lightened. Where readings to 10″ are desired, as in nice astronomical work, the radius should be about 7½ inches, and the instrument, to be strongly built, should weigh about 3½ pounds.

The parts of an instrument should move freely, without binding or gritting. The eyepieces should move easily in the telescope tubes; the bracket for carrying the telescope should be made very strong. It is frequently found that the parallelism of the line of sight is destroyed in focusing the eyepiece, either on account of the looseness of the fit or because of the telescope bracket being weak. The vernier should lie close to the limbs to prevent parallax in reading. If it is either too loose or too tight at either extremity of its travel, it may indicate that the pivot is not perpendicular. The balls of the tangent screw should fit snugly in their sockets, so that there may be no lost motion.

Where possible, the sextant should always be submitted to expert examination and test as to the accuracy of its permanent adjustments before acceptance by the navigator.

254. Resilvering Mirrors.—Occasion may sometimes arise for resilvering the mirrors of a sextant, as they are always liable to be damaged by dampness or other causes. For this purpose some clean tin foil and mercury are required. Upon a piece of glass about 4 inches square lay a piece of tin foil whose dimensions exceed by about a quarter of an inch in each direction those of the glass to be silvered; smooth out the foil carefully by rubbing; put a small drop of mercury on the foil and spread it with the finger over the entire surface, being careful that none shall find its way under the foil; then put on a few more drops of mercury until the whole surface is fluid. The glass which is to be silvered having been carefully cleaned, it should be laid upon a piece of tissue paper whose edge just covers the edge of the foil and