A HIGH-PRECISION PRISMATIC ASTROLABE

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The equal-altitude method, which enables maximum elimination of the various causes of errors usually encountered in the determining of zenithal distances, is consequently capable of great accuracy and considerable usefulness in positional astronomy work.

We have already had occasion to show (5) the promising results that may rightfully be expected in the determination of latitudes. If when applying the method recourse is had to instruments equipped with a device eliminating the personal equation of the observer, a comparable accuracy may be anticipated in the determination of local time.

Many types of instruments may be devised for observing the equal altitudes of stars. In the *Hydrographic Review* for 1935 (1), my late lamented colleague and friend, Mrs Chandon, and I described most of those which were either suggested or in use at the time. All were field instruments intended, depending on their accuracy, for reconnaissance astronomy or geodetic astronomy.

Since then two new instruments have been designed which show an appreciable improvement over their predecessors. One, the Willis pendulum astrolabe, is yet another field instrument of a highly portable type; the other, Danjon's impersonal astrolabe, which is capable of a high degree of accuracy, is suited to large astronomical observatories, where it seems destined to replace meridian and zenithal instruments.

The main object of the present article is to acquaint readers of the *International Hydrographic Review* with Danjon's apparatus; a brief description of the Willis instrument has previously appeared in this same journal (3).

A few additional details concerning this latter instrument may be of interest, however, with particular regard to its origins.

At the time of the international project of revision of longitudes, in 1933, I was in charge of the observations made with the prismatic astrolabe (large S.O.M. model) at San Diego, California. A meridian instrument was also being used there by Messrs. Chester B. Watts and John E. Willis, astronomers at the U.S. Naval Observatory. Two years later, when the article on equal-altitude instruments appeared in the *Hydrographic Review* (1), I sent them a copy in token of our friendly cooperation. Mr. Willis, who at San Diego had shown considerable interest in the use of the prismatic astrolabe, took particular note of the Baume-Pluvinel bent telescope, which the above-mentioned article described, and whose

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(1) The numbers in brackets refer to the bibliography appended to this article.

difficulties of application were discussed. As this instrument, in contrast with all other equal-altitude instruments, does not make use of double reflection to obtain an unvarying optical right angle, absolute constancy of the distance between the mercury trough and the eyepiece and object-glass of the telescope was required. Attracted, however, by the simplicity of the principle of the bent telescope, Mr. Willis attempted to remedy its faults, and by substituting a horizontal, pendulum-suspended mirror for the mercury trough, thus achieved his « pendulum astrolabe ». I must admit to a great many reservations at that time as to the potential accuracy of this instrument (4), as I found it difficult to accept the fact that a 20-centimetre pendulum might supply a definition of the vertical comparable to that of the mercury trough. I was not really convinced until the analysis took place of various observations carried out in France with the pendulum astrolabe (6).

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It nevertheless appears that no very high accuracy value can be achieved with such an instrument, in view of the fact that single reflection is used. A parallel may be drawn in this connection with the types of instrument used for measuring altitudes at sea (8); it will be recalled that in 1666, Hooke built a mirror instrument for observations of this kind, but they could not be carried out efficiently until about 1700, when the conventional sextant, which makes use of double reflection, was developed according to Newton's indications. The superiority of double reflection is considerable, when the observer is mobile; it disappears in theory when the instruments are set up at a fixed station. Consideration must nevertheless be given to the fact that when extreme accuracy is sought all the theoretical instrumental conditions are not absolutely fulfilled, and that residual errors of observation are the result; these are less appreciable in double reflection instruments, and in developing an equal-altitude instrument for astronomical observation purposes, Danjon was unquestionably right in using the conventional prismatic astrolabe as a basis (1).

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Two major defects of this instrument prevent, however, taking full advantage of its remarkable qualities, which essentially consist in the accuracy with which the direction of the celestial body is referred to that of the zenith by means of reflection of the star in a mercury trough, and in the excellent stability of the prism angle.

The first of these drawbacks derives from the method of observation by coincidence of both the direct and reflected images supplied by a particular star : the noting of the times of coincidence is affected by the personal equation of the observer; moreover, only one sight is taken per star, with an accuracy which is far inferior to that obtained in the definition of the instrumental altitude of observation, so that in order to eliminate the random error of sighting in such a way as to derive the maximum benefit from this instrumental accuracy, each set of observations must include a large number of stars, involving laborious computations in the preparation and reduction of the observations.

The second drawback, which we explained, apparently for the first time, in 1935 (2), derives from the fact that the zenithal distance of observation not only depends on the angle of the prism, but likewise on the focussing of the eyepiece,

(1) Designed by A. CLAUDE, Calculator at the Bureau of Longitudes, and L. DRIENCOURT, *Ingénieur Hydrographe*, in 1905.

which, although locked in place, may vary slightly during a series of observations, due in particular to fatigue of the observer.

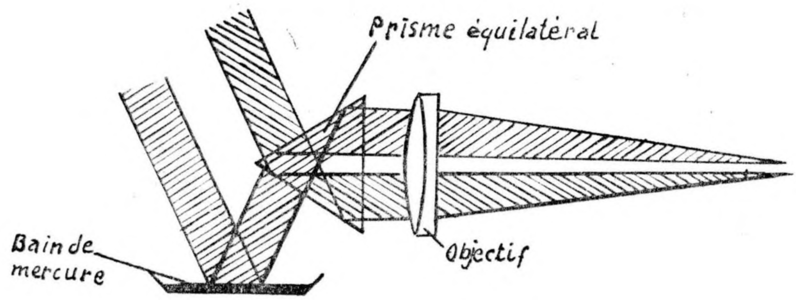

Fig. 1.
Path of rays in conventional prismatic astrolabe.

Various devices have been designed to mitigate either one of these defects, but none has been largely used in practice. Some eliminate the personal equation by the interposition of thin plates placed along the path of the light rays and actuated by a motor in such a way as to enable the observer to maintain the coincidence in altitude of the two stellar images during a certain interval, when electric contacts controlled by the mechanism actuating the plates produce signals corresponding to various well-defined altitudes of the star on the band of a recording chronograph. The others, connected with the defect of the equilateral prismatic astrolabe, make the two pencils of light relating to the two stellar images coaxial by substituting systems of mirrors or semi-silvered prisms, assembled as rigidly as possible, for the single prism. This arrangement, however, does not appear to favour the strict retention of the instrumental zenithal distance.

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Danjon succeeded in eliminating both defects simultaneously by using a bi-refractive system (Wollaston quadruple prism), in much the same way as the mobile plates of the impersonal device alluded to above, but with the added advantage that, when the angle of cut of the bi-refractive device is accordingly calculated, the beams produced by this optical system have parallel axes, and the coincidence of the stellar images at a given instant consequently no longer depends on the focussing of the eyepiece.

Furthermore, he adapted this device to a large-size prismatic astrolabe of special design, as experience had shown that, all things being equal, the accuracy of determinations increases with the size of the instrument (5).

Danjon first built a prototype equipped with a 6-cm prism associated with a telescope of 70-cm focal length; he then had the *Société d'Optique et de Précision* of Levallois (O.P.L.) construct a final version with a 10-cm prism and a telescope having a focal length of 100 cm. It is this O.P.L. instrument, of which an initial model is now in use at the Paris Observatory, which we shall proceed to describe in its essentials. All its features have been studied is such a way as to produce the best results (9).

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The 10-cm equilateral prism placed in front of the object-glass is fitted similarly to that of the conventional S.O.M. astrolabe, and is similarly adjusted by auto-collimation. The adjustment system with regard to the horizontality of the edges, however, is much more finely geared, in order to enable the operator to regulate precisely the distance between the pair of stellar images.

The telescope, whose object-glass is also 10 cm in diameter, and whose compound eyepiece is capable of 175 magnification, is bent three times between the object-glass and eyepiece by means of two parallel mirrors and a small equilateral prism. This arrangement, which presents no drawbacks in view of the fact that observation is effected by image coincidence, has the advantage of considerably reducing instrument space, and moreover enables the mercury bath to be brought closer to the vertical axis of rotation, thus appreciably decreasing disturbance of the trough when the telescope is shifted in azimuth.

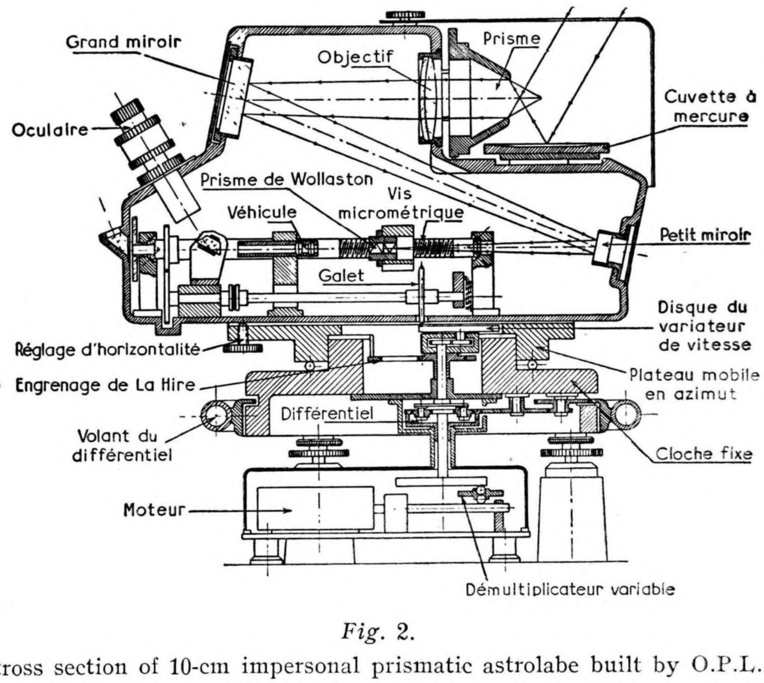

Fig. 2.

Cross section of 10-cm impersonal prismatic astrolabe built by O.P.L.

A diaphragm placed in front of the object-glass exposes two crescent-shaped entrance pupils whose purpose is to supply diffracted images elongated as little as possible in a vertical direction, and possessing two axes of symmetry even in the case of imperfect focussing; another object is to eliminate the light-rays passing through the equilateral prism near its edges.

A reticle in the plane of the final image consists of four horizontal wires used as a guide for evaluating coincidence in altitude of the pair of star images, and four vertical wires enabling the evaluation of the pair's position with reference to the field-centre, in order that the measurements may be corrected in case centering of the observation is inadequately achieved.

Danjon also made every effort to obtain a mercury trough whose reflective surface would have all the optical properties of a flat mirror. The form, type and size of the trough, its cleanliness as well as that of the mercury, are all of considerable importance, and great care must be taken in using the bath in order to obtain an excellent definition of its surface and horizontality.

We shall now discuss the characteristic feature of the instrument, i.e. its impersonal device, which, as previously stated, moreover renders the beams producing the stellar images appreciably parallel. The birefringent prism used is a Wollaston quadruple prism (Fig. 3), which supplies two additional images A_1 and A_2, B_1 and B_2 for each of the two stellar images A and B (Fig. 4), polarized in right-

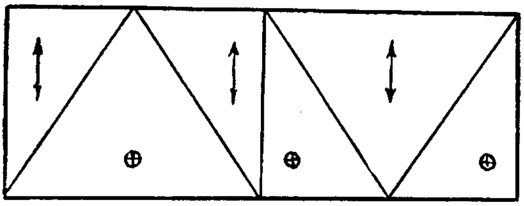

Fig. 3.

Diagram of Wollaston quadruple prism.

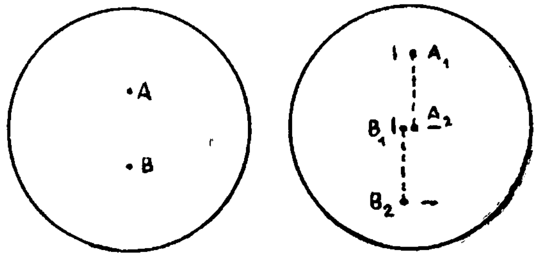

Fig. 4.

Images produced by birefringent prism.

angled directions. By shifting the prism parallel to the axis of the telescope, images A_2 and B_1 can be made to coincide. As distance AB varies under the influence of diurnal motion, the coincidence of A_2 and B_1 can only be maintained by giving the birefringent prism translatory motion. Moreover, for greater convenience of observation, images A_1 and B_2 are masked by a special screen.

The Wollaston prism is placed in the axis of the telescope in front of the small equilateral prism directing the light-rays towards the eyepiece. It rests on a carriage actuated by a micrometer-screw parallel to the telescope axis. The screw can make twelve full rotations, each corresponding to a variation of about 26'' in the zenithal distance of the celestial body; at Paris, the time of observation allowed by the twelve rotations is 28 seconds for stars sighted in the prime vertical.

At each rotation of the screw, two electric contacts inserted in the circuit of a recording chronograph are closed and broken; the recorded signals indicate the times of passage of the star at various well-defined zenithal distances. The use of such successive circuit-closings and openings enables the screw's rotations in either direction to be applied without error. A simple device reduces the number of rotations to 6, but with four contacts per rotation, in the case of the observational field of stars near the meridian, whose motion in terms of zenithal distance is very slow.

In spite of all the optical systems, whether refractive or reflective, interposed in the path of the light rays, the instrument enables the observation of stars up to magnitude 6.1.

The micrometer-screw is actuated by a motor operating at constant speed and placed under the astrolabe, in a hollowed-out space at the top of the observation pillar. It is powered by 12-volt direct current. The screw is driven by means of an extremely ingenious speed-varier, using a La Hire gear, which automatically and to within very narrow limits, ensures a speed of rotation of the screw corresponding to the azimuth in which the telescope is oriented, and proportional to the sine of the azimuth. Both stellar images are thus maintained very close to coincidence; all the observer needs to do in order to achieve absolute coincidence is to correct the motion of the screw slightly, by means of a differential controlled by a wheel of large diameter and hence of great sensitivity.

Actuation of the driving mechanism and of the various controls produces no appreciable vibration of the mercury bath, which is only noticeable when the instrument is being adjusted in azimuth.

The position of the micrometer-screw which corresponds to non-duplication, i.e. to the instrumental height which produces image coincidence in the conventional astrolabe, is extremely stable in the O.P.L. astrolabe, the telescope of which is cased in cast iron. The prototype of the instrument, on the other hand, showed slight variations with temperature, which was attributed to abnormal thermic behaviour of the object-glass and of the aluminium casing then used.

Great pains have likewise been taken with the housing of the instrument. The movable roof exposes the astrolabe completely, and the opening is sufficiently large to admit air from the outside, thus preventing the images from being distorted by the warm air rising from the inside. In spite of its size, the opening does not allow the wind to affect the surface of the bath, which is adequately protected by the baffler placed over it.

It may finally be added that the impersonal astrolabe benefits from the simplicity of operation applying to equal-altitude instruments. The observation pillar requires no firm foundation. The instrument, which weighs 175 kg, complete with accessories, may be set up and adjusted within two or three hours. It is therefore suited to temporary observatories as well as to the large permanent ones.

Numerous series of observations have been carried out at the Paris Observatory both for the purpose of perfecting methods of observation and computation and in order to investigate systematically the possible continuing existence of former errors or the introduction of new ones, such as a residual personal equation of the observer, a colour equation resulting from chromatism of the Wollaston prism (although, for reasons of symmetry, chromatism effects should compensate one another), and lastly an equation of magnitude, deriving from the elongated shape of the stellar images and from variations in their size according to the brilliance of the star being observed.

No such equations have been discovered.

At one time it was believed that an equation of azimuth corresponding to a variable reaction of the observers depending on the speed of vertical displacement of the stellar images had been found, but further analysis of the results obtained showed that a systematic error of the right ascensions of the stars as against declination was involved.

Thus trials carried out have not only served to show the large amount of accuracy attained in determinations of latitude and time, but have proved that the instrument is moreover capable of revealing errors, lack of homogeneity and distortions in the star catalogues (10, 11).

With regard to accuracy, here are the square errors derived from internal agreement, after elimination of the catalogue errors :

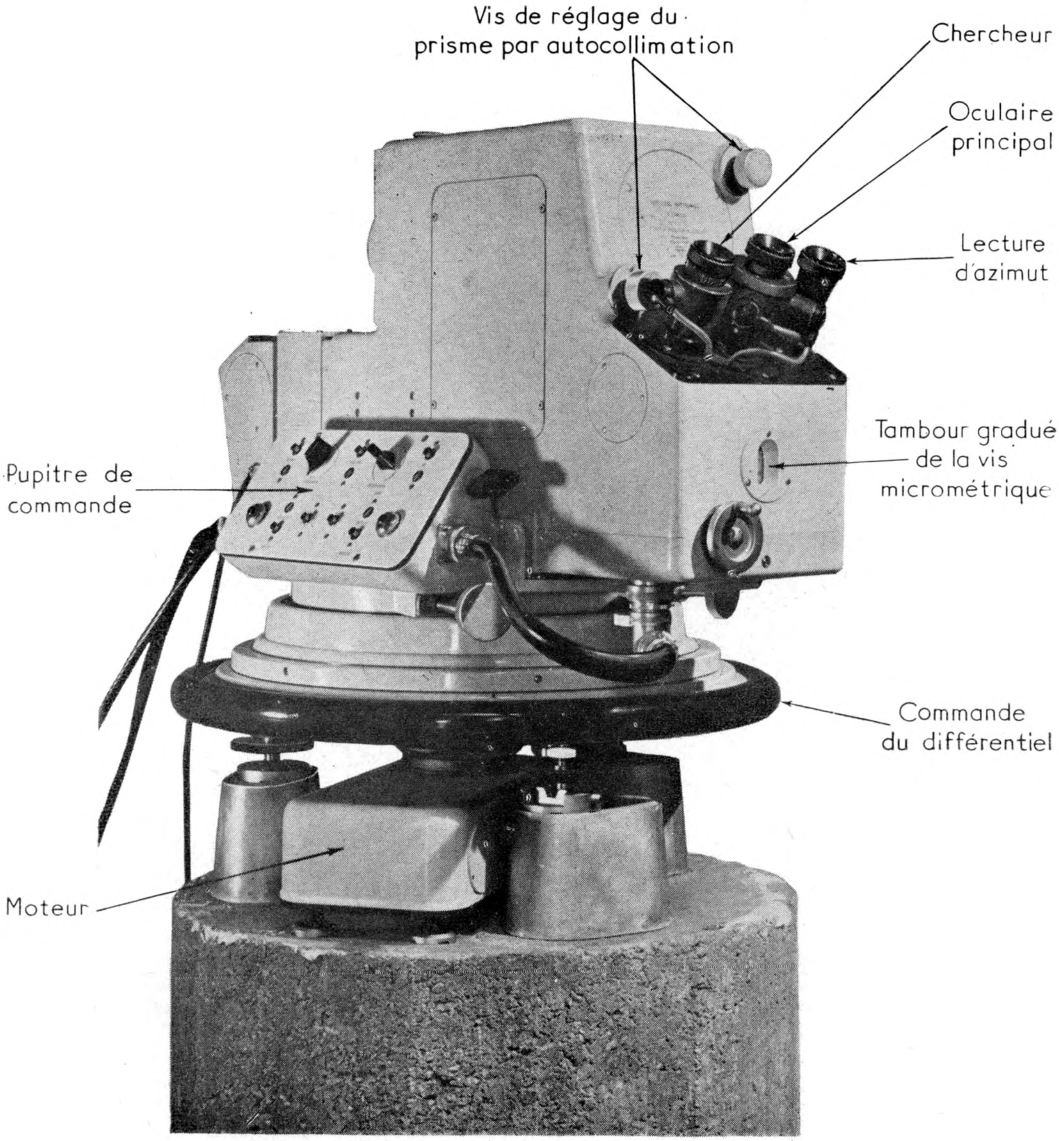

Fig. 5.

Danjon's impersonal prismatic astrolabe, built by O.P.L.
General view (without equilateral prism).

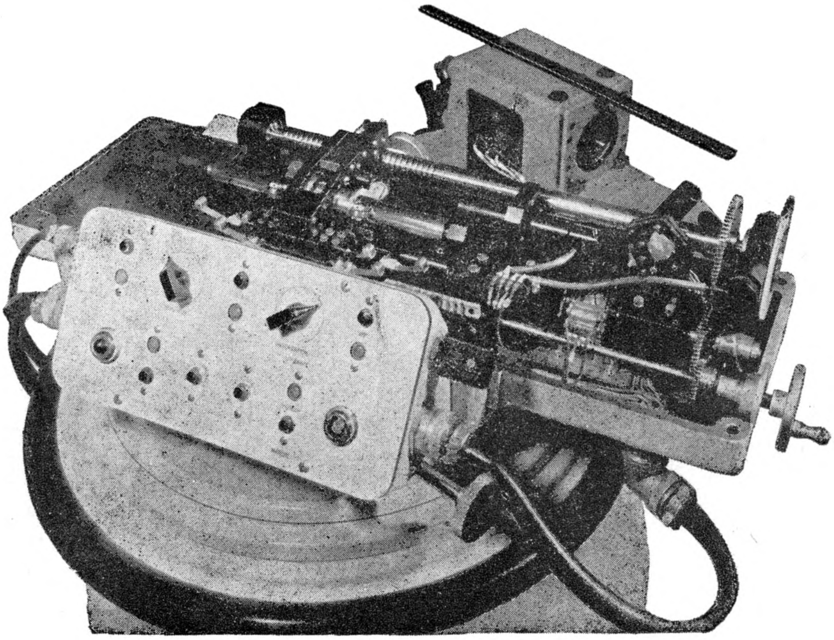

Fig. 6.

Danjon's impersonal prismatic astrolabe, built by O.P.L.
Driving mechanism of micrometer.

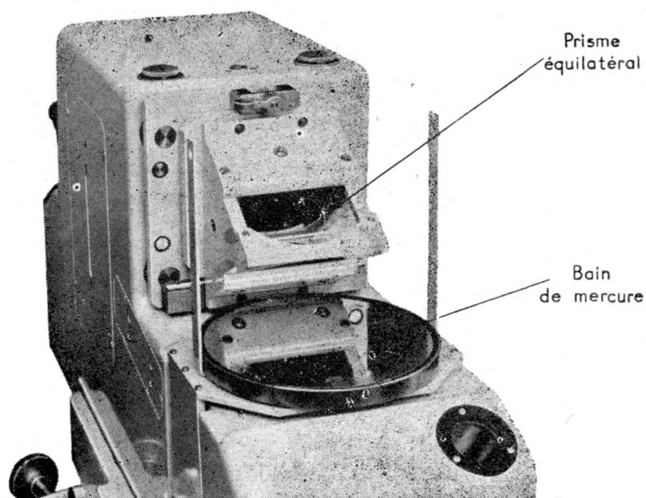

Fig. 7.

Danjon's impersonal prismatic astrolabe, built by O.P.L.
Front of telescope.

Most frequent value of the standard discrepancy of an isolated observation.. 0.17"

Mean square error in time......................	0.004"	per series
Mean square error in latitude....	0.05"	of 28 stars

These values are confirmed by external agreement.

The O.P.L. prismatic astrolabe has been in regular use at the Paris Observatory since July 1956, following a trial-period of three months. It contributes normally to the determination of time and to the study of latitude variation.

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The results obtained show that the Danjon impersonal prismatic astrolabe is a considerable improvement over the conventional instruments used at astronomical observatories. Of all those which enable geographical latitudes to be obtained, it is without question the instrument supplying the best results; as regards the determination of time, it is only rivalled by the large zenithal photographic telescopes. Hence, in spite of its great simplicity of use, the new prismatic astrolabe may be regarded as the most accurate among modern positional astronomy instruments.

All persons interested in the method of equal altitudes were well aware of its fascinating possibilities, since it made use neither of a spirit level, nor of graduated circles, and enabled the observation of bodies several hours away from meridian transit, but it was necessary to await Mr. Danjon's achievement before all these advantages could be applied with complete efficiency.

The availability of this instrument now enables astronomical observatories to determine time with increased efficiency, to improve the coordinates of stars, and to play an important part in the study of polar shifts (7).

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