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PRINCIPAL ADVANTAGES AND STRUCTURAL FEATURES OF A HORIZONTAL MERIDIAN INSTRUMENT

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/Figures referred to herein are appended./

A review of astrometrics in the last 50 - 70 years shows that, in spite of great progress in the theoretical field, improved methods, and great accumulation of observational data, the systematic errors of observation remain practically at the same level, namely in the range 0.2" to 0.4". The reasons for such a long standstill in the field of improving accuracy cannot be accidental; and so long as they are not made public and exhaustively analyzed, it is useless to expect further progress in this direction.

As is well known, the precision of astrometrical observations is governed by three principal factors: the condition of the earth's atmosphere, the quality of the astrometric instrument, and the characteristics of the recording apparatus (eyepieces and photographic plates or photoelements). In this article we shall critically examine the weak points of present-day astrometrical instruments, not dwelling on their specific role in specialized operations, as in the case of vertical and meridian circles, transit instruments, etc.

Errors Associated with Graduating a Circle

Normally, a circle has 10,800 or 21,600 divisions. In the most favorable instance, individual corrections are determined for only a few hundred of them. In the case of the very large number of remaining marks, from which readings are actually taken, corrections are averaged according to a curve describing the behavior of errors in the investigated arc of the circle. Thus, the calculation of errors in the position of the marks is basically statistical, and even then errors can only partially cancel by means of a very large number of observations. But even numerous observations cannot completely eliminate error, since in determining the declination (altitude)

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of a star not more than 32 marks are used, among which there may not be a single mark with an individual correction. It may be said without exaggeration that each instrument must give its own "system" of star positions.

The quality of the marks drawn upon silver does not permit tracing lines for microscopic reading with a linear error less than 0.5 - 1 micron; in case of a glass circle, it gives an error not less than 0.2 - 0.5 micron. These errors are approximately equal in effect since metal circles are about one meter in diameter and glass circles are about 40 centimeters. (Here we are not taking into consideration the difficulty of uniting glass and metal in high-temperature intervals.) In terms of angular measure, this linear error gives an error of 0.2" to 0.4" for both cases. In astronomical practice the error is closer to the latter figure, 0.4".

Errors of a "Curved" Tube

The problem of tube curvature is one of the most difficult in astrometric practice. This is completely natural, inasmuch as "curvature" depends, in one way or another, on the following factors:

1. The form and elastic properties of the material of the tube and the tube's position relative to the direction of gravitational force;

2. Temperature, influencing the dimensions and elastic properties of the tube;

3. Deviation of the optical axis of the objective relative to the geometrical axis of the tube, and the relative displacement of the object glass due to a difference in coefficients of thermal expansion and to the different thermal conductivity of the materials. Errors of this sort are not compensated by displacement of the center ocular wire grid, where, during temperature change, the symmetry relative to the tube axis should not be disturbed. (Preliminary calculations have indicated that errors due to relative displacement of the object glass in the course of a day during unfavorable conditions may amount to a tenth or more of an angular second.)

4. Local heating of parts of the instrument, due to the heat radiated by the observer. This influence would be especially strong during cold weather and also during observation of stars at the zenith, when the observer is located beneath the instrument and a current of warm air flows up around it; this heat may also affect refraction.

At present, the appearance of "curvature" is one of the chief obstacles to increasing the optical strength of meridian instruments.

Nonsimultaneity in Determining the Collimation Error and the Inclination of the Axis During Observations

Corrections, introduced during observation, for collimation errors and inclination of the axis are chiefly based upon the preliminary study of pivot forms. The form of the pivot is necessarily adopted once and for all, and is independent of considerations of time, temperature, and other conditions accompanying observation. Chance errors due to dust in the bearings, congealing of lubricant, etc., are not considered. It can be assumed that, for example, the congealing of the lubricant due to temperature decrease may introduce considerable error. For small, specific pressures between the pivot and bearings customarily used in astrometric instruments, the congealed lubricant may not flow sufficiently from the space between the bearing surfaces, and the instrument will "swim." This floating introduces a certain indeterminateness in its position. In instruments of ordinary construction it is difficult to detect and correct these errors.

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Such, in a short outline, are the basic shortcomings in astronomical instruments of the present time. These shortcomings hinder the wide application of objective methods of recording phenomena, inasmuch as they effectively limit the weight and dimensions of any recording equipment set on the movable part of an instrument.

Consideration of Basically New Designs

Now that we have established the causes that hinder further accuracy and refinement in determining stellar coordinates by meridian instruments, we can contemplate various schemes for instruments which are to a considerable extent free of the above-mentioned shortcomings. This article will describe one such system.

Basically, the system consists of a plane mirror rotating about a horizontal axis, in conjunction with a rigid tube. From the history of astronomical instruments it is known that such an idea was first conceived by Bauffart in 1682; but a practical statement of the problem concerning this combination for accurate astrometric measurements became possible only much later, thanks to experience gained during work on transit instruments with the Bamberg-type articulated tube, in which a prism, inserted between the objective and the filar grid, acts as a reflector. Practical application also had to await improvement in the metallurgy of stainless steels and for other technical improvements.

Professor N. N. Pavlov of the Pulkovskiy Observatory became convinced of the expediency of operating transit instruments possessing a rotating reflector and rigid tube, and proposed his own design for such an instrument. (N. N. Pavlov, "Photoelectric Recording of Star Passage," Izvestiya AN SSSR, 1937, p 662. A. A. Ilinich raised the question of applying this principle to a meridian circle.

The author of this article studied this question in 1924; only after a lapse of 20 years, however, did he find it possible to begin work, which included the following investigations: determination of right ascension, time correction, and the deviation of stars. However, the possibility of determining separately the coordinates and partially the zenith observations was not excluded. Further discussion will be devoted to one of the attempts to make a rational solution of this problem.

Figure 1 shows the basic scheme of a horizontal meridian instrument with the following designations:

G is the plane reflector with a central aperture, rotating about the horizontal axis ZZ';

T(S) and T(N) are the main tubes, south and north (corresponding to the indices within the parentheses);

O(S) and O(N) are the objectives of the main tubes;

F(S) and F(N) are the focal planes of the objectives O(S) and O(N);

M(S) and M(N) are the south and north illumination sources;

OM(S) and OM(N) are the collimator lenses;

C and C' are the rings of the instrument;

O'(S) and O'(N) are the objectives of the autocollimation tubes;

O'K(S) and O'K(N) are the eyepieces of the autocollimation tubes;

P and P' are pentaprisms;

L and L' are bearings; and

H is the floating horizon.

We will begin the review of the diagram with a discussion of the optical paths.

The light rays from the star under study are incident upon the mirror G and are refracted by either lens O(S) or O(N) as one chooses. Let us assume that they are reflected in O(S), as shown in Figure 1. Refracted by the lens, these rays form a real image of the star on the focal plane F(S), where the star is actually observed. The zenith interval is read on circles C and C', to which we shall return.

Let us consider for a moment the problems concerning the azimuth control of the main tubes, the calculation of the axis movement of the main reflector G, and the determination of the nadir point on the circles.

The main tube's change in azimuth can be determined at the moment directly preceding or following observation. For this purpose, a collimation lens OM(N) is placed in front of the illumination source M(N). This lens reflects the illumination source on the surface F(N) at the intersection of the wires of the ocular grid (during this time, the eyepiece is moved aside). The objectives O(N) and O(S) transfer this image (through an aperture in the main mirror) to the focal surface F(S) along the optical axis or close to it. Measurement of the amount of fluctuations in azimuth of tube T(S) can be made with the same ocular micrometer which is employed for stellar observation. The illumination source at the time when the star is being observed can be extinguished from the eyepiece with the help of a key which switches off the illumination lamp.

Control of the axis position of the main mirror during observation is also possible if this matter is considered during the design of the mirror. It is very important that the connection between mirrors and axis ZZ' be reliable. For this purpose, the mirror may be of stainless steel (or any other alloy of high reflection capacity and the necessary mechanical properties) cast as a unit with the axis ZZ'. In this case, the ends of the axis can be polished and employed as mirrors which may be regarded firmly bound up with the main mirror.

After we have set up a pentaprism in front of this butt mirror and set up behind the pentaprism an autocollimation tube K(S) with an eyepiece O'K(S) drawn out toward the observer, we look into it in the direction of the ray reflected by the end of the axis ZZ' and at any moment it is possible to judge the change in direction of axis ZZ' relative to a certain reference position. The presence of two main tubes in conjunction with a floating horizon makes it possible, as indicated by theoretical investigations, to solve fully the problem concerning the movement of axis ZZ' and to determine its position at any moment that the observer desires, without consideration of pivot form.

Nadir position on circles C and C' can be determined with the help of a mercury level, which is slightly modified by introducing into the mercury a flat glass mirror acting as an artificial horizon. This artificial horizon -- let us call it "floating" -- will give a better image as compared with the usual mercury one with its constantly moving surface. In addition, the high position of the centroid of the floating mirror above the mercury level will contribute to the whole system compensating features in regard to obviating horizontal disturbances (of a seismic or some other nature) which are transmitted to the mirror by the mercury. Actually, in the presence of such disturbing forces, frictional forces arise between the mercury and the floating part of the mirror; and there arises an inertial force that rotates the mirror in the direction of rotation of the mercury surface, which in its turn tends to rotate the mirror in the opposite direction. To bring the upper surface of the mirror into a parallel position with the mercury surface is difficult to accomplish, if in this manner one seeks to impart an ideal geometric form and severely uniform thickness to the mirror. It is much easier to achieve this by creating the necessary conditions of equilibrium, which is done be removing material from the side of the more protruding part. Any remaining declivity, if technically impossible to eliminate, can be cancelled during observations by rotating the mirror 180 degrees.

Above we have only considered the negative aspects of present-day circles, the practical impossibility of investigating individual inaccuracies in graduation marks, and, finally, the insufficient accuracy in placing in coincidence the micrometer filar wires and the marks. From the standpoint of principles, circles preferably should have a small number of marks, which permit making adjustments for each of them, and have a micrometer arrangement for measuring within an interval of one division.

About 12 years ago, while investigating precision-measuring instruments, the author discovered a way of obtaining and utilizing a physical straight line, which is undistinguishable in any practical way from a geometrical straight line and which permits one, under specific conditions, to transfer from a geometrical combination of the micrometer filar wire to photometric "division" /bissitsirovanie/, obtainable on the principle of field-levelling and greatly increasing the accuracy of placing lines in coincidence. This straight line serves as an edge for the metallic prism, which is polished with optical precision. If the reading microscope (Figure 2) is directed on the edge of such a prism (at an angle of about 90 degrees), aligning the axis of the microscope with the bisectrix of the prism angle, and if one utilizes special vertical illumination, then the light incident on the prism is reflected from its face in directions perpendicular to the original direction, but on the edge of the prism will be seen a bright line which is due to the insignificantly small curvature of the edge and to diffraction phenomena. If the filar wire of the ocular micrometer is placed in coincidence with this line, then the line will seem to be completely covered and only the narrow gaps along the side of the filar wire will be visible (shown in Figure 2, in the circle). Under these conditions, the slightest movement of the filar wire from the axis abruptly cuts out the gap on one side and increases it on the other.

Tests conducted in 1934 - 1936 showed that the mean square error of one-line coincidence is equal to 0.026 micron by laboratory measurements. The last measurements of this kind were made in 1945 and are set forth in Table 1 where columns 1 to 10 are independent series of measurements. They are expressed in the divisions on the cylinder of the wedge-shaped micrometer and are combined in three groups (series 1 - 5; 6 - 9; 10) depending upon the circumstances under which they were obtained (each case is described in the note following the table). A comparison of these data with the data of placing in coincidence the mark on the glass indicates the possibility of increasing measurements five to ten times.

The practical application of this idea in meridian instruments involves the form of a toothed circle resembling a toothed ring. Figure 2 illustrates the toothed ring in connection with the reading microscope and the special vertical illuminator. The teeth should be one degree apart and the error in position for each should be determined. The lengths of the degree interval can be measured by a wedge-shaped micrometer. This instrument was employed successfully by the author for similar work, since the relative accuracy of the measurements will not exceed 10^{-5} if one obtains readings up to 0.03" - 0.04".

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The problem of the "toothed" circle cannot at present be considered as definitely solved, since the author has had to limit himself to a test of only one element of the toothed circle. In view of the importance of this problem, however, it deserves a very energetic treatment in the immediate future. The "toothed" circle may be made of stainless steel.

Table 1. Errors During Repeated Applications Made by a Wedge-shaped Micrometer Under Various Conditions

NOTE: Readings are given in divisions of the cylinder of the micrometer screw, while the mean square error of one application is given both in cylinder divisions and in fractions of a micron.

	Series Number									
	1	2	3	4	5	6	7	8	9	10
Average reading	6.0	1.2	3.8	3.0	9.7	6.0	3.4	9.4	9.5	9.3
Mean sqaure error of one coincidence reading										
In divisions	0.14	0.17	0.12	0.16	0.09	0.39	0.35	0.49	0.38	0.49
In microns	0.025	0.032	0.022	0.029	0.016	0.070	0.063	0.088	0.068	0.017

NOTE: Series No 1 - 5. The coincidence readings were made very carefully but with weak illumination of the prism ridge of the wedge-shaped micrometer. The value of one division on the micrometer cylinder is 0.18 micron. Series No 6 - 9. The coincidence readings were made quickly and not especially carefully (attempts to obtain results close to the probable manufacture's results). The value of one division on the micrometer cylinder is 0.18 micron. Series No 10. Measurements were made after the ridge of the prism was polished, which gave a good result. Series No 10 was made especially carefully. The value of one division on the micrometer cylinder is 0.034 micron.

The stumbling blocks in the way of developing present-day meridian instruments, as we have seen, are the "curved" tubes. In our case, the problem of curvature extends only to the main flexible mirror. Preliminary calculations indicate that with a ridge design on the mirror and with a 1:15 ratio of width to diameter, the mirror's curvature exerts less obvious influence during observations than the tube's curvature. There are ways of decreasing it in the future.

The installation of lens and ocular network directly on the foundation opens new possibilities. The lens diameter can be increased at least by 250 - 300 millimeters and later increases can parallel the growth of technical possibilities of preparing large all-metal moveable mirrors. The gaps between the objective lenses can be increased to a dimension necessary for creating more advantageous conditions for heat exchange in the intralens gaps with the outside air. An increase in diameter of the objective will make it possible to try in practice the single-lens aspherical objectives in combination with an ocular light filter for excluding the influence of atmospheric dispersion on measurements. Such objectives are free of the errors possessed by a double-lens objective in connection with the relative shift of the lenses with temperature changes, unavoidable even with a small difference in coefficient of thermal expansion and heat-conduction components. The fixed ocular part opens an unlimited field for applying objective methods of recording phenomena in regard to size and weight of the recording apparatus.

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To sum up, we see that the horizontal design of the instrument possesses a number of important advantages over instruments with flexible tubes. The most important of them are: (1) the possibility of calculating, during observation, the errors due to variations in the position of the tube's optical axis and the mirror's rotational axis, (2) reduction in the error of calculating angles, (3) improvement of the conditions for applying objective methods of observation, and (4) important reduction of the influence of curvature and the resulting increase in the optical power of the instrument.

An unavoidable peculiarity of the system is the presence of two tubes, since one cannot perform observations along a meridional arc greater than 120 - 130 degrees.

Space does not permit examining the many questions of interest, such as: further reduction of mirror curvature, strengthening lenses in large objectives, investigating horizontal refraction, etc.

Modern metallurgy and optical technics possess the necessary tools for successfully solving the problems of preparing a horizontal meridian instrument, but they still must solve great problems of improving precision, which require skill and technology for solution.

The scheme of the horizontal meridian instrument which we have examined is not, of course, ideal. The combination of metal and glass is a complex matter, since both have completely different thermal conductivities and consequently react with different rates to changes in atmospheric temperature. At present, there is still no completely definite prospect for solving this problem.

[Appended figures follow.]

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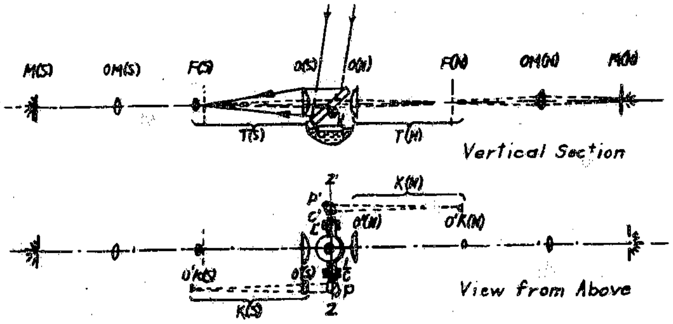

Figure 1

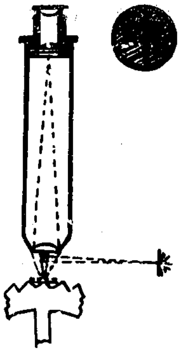

Figure 2

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