An improved polarizing microscope.
IV.[1] The Fedorov stage (three-axis).

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INTRODUCTION

IN the microscope designed by G. B. Amici (1844), which seems to be the very earliest polarizing microscope, the stage already possessed not only graduated concentric rotation, but also a horizontal tilting axis. It was, in fact, a built-in two-axis universal stage. Glass hemispheres were introduced at a much later date by W. G. Adams (1875) for use in a specially designed conoscope, but the Adams stage seems to have been little used (see, however, H. Schumann, 1949).

The two-axis stage as now known was designed by E. S. Fedorov (1893) and was soon followed by other forms. It is a curious fact that the four-axis stage was used almost from the beginning, though it was for some time known as the three-axis stage. For example, the Swiss stage figured as a three-axis type by Duparc and Pearce (1907, vol. 1, p. 283) has four axes, and Nikitin, even in 1936 (p. 9), describes a four-axis diagram as the three-axis stage. There seems never to have been a separate early development of the three-axis stage in the strict sense, as now to be described, though a great part of the procedure for the four-axis stage really relates to three axes, the fourth axis being locked at the 90-degree position.

The explanation of this rather unexpected course of evolution can probably be found in Fedorov's original announcement of the three-axis design. There are two possible arrangements of the two inner axes, one having the tilting axis outside the concentric movement, as now, and the other with the tilting axis *inside*. When Fedorov first realized the importance of adding a third axis it was the second, unfamiliar and relatively useless, form that he illustrated (1896, p. 241). The inconvenience

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of this design must have been obvious at once, especially since an inner concentric movement was already in use on the two-circle stage. Accordingly, an inner concentric movement seems to have been added, the result being a four-axis stage of the type used ever since. Development of the three-axis stage was, in effect, bypassed by way of the useless alternative form. Berek (1924, p. 21) says that the rapid development of the four-axis stage took place in the workshop of R. Fuess by the co-operation of Fedorov, C. Leiss, and C. Klein in the years 1895–98. Berek numbered the axes from within outwards A_1–A_4, A_5 being the axis of the microscope stage. This nomenclature will be used in the present paper, A_3 being of course absent in the three-axis stage.

In recent years the addition of a fifth axis by R. C. Emmons has provided an elegant means of eliminating computations, but the additional movement brought with it some loss in stability, and side by side with this development there has been a reverse trend in favour of the increased rigidity and simplicity obtainable with fewer axes. The two-axis stage, though widely useful, is not completely adequate, since it permits only the alinement of any chosen direction with the axis of the microscope but not the maintenance of a chosen plane. With the three-axis stage, however, it is possible to bring the normal to any desired plane into coincidence with the horizontal axis of the universal stage; by this means the crystal can be rotated so that all directions in the plane pass successively into line with the microscope axis. This is the arrangement necessary for the identification of an optical symmetry plane, an adjustment which forms the basis of ordinary universal stage procedure. The fourth axis (i.e. the outer concentric movement, A_3 of Berek) gives little further advantage, for it represents only a step in the direction more fully realized with five axes; it enables a setting to be made mechanically for which co-ordinates would otherwise have to be calculated or measured on the stereogram. It follows that if the stereographic projection is accepted and used as an integral part of the procedure, a three-axis stage will be adequate.

The importance of the three-axis stage has been very clearly defined by C. M. Gilbert and F. J. Turner (1949); they also specially stress the value of the stereographic projection not only for computation but to provide 'a clear picture of the optic and crystallographic orientation of the mineral'. So far as the writers are aware, the only three-axis stage made, up to the present, is that by the firm of Silge and Kuhne of San Francisco to a design which in all other respects closely follows the existing four-axis pattern.

It may be asked what advantage can be gained by the omission of the relatively simple outer concentric axis. The disadvantages are small, for it is rarely used even in standard four-axis procedure. In the model now to be described, by fixing the tilting axis A_2 at right angles to A_4 it has been possible to eliminate collisions between the Wright arcs and the objective. Consequently the arcs have been fixed upright, without hinges, and the lock to the spindle A_2, universally recognized as inefficient, has been replaced by clamps that slide on the Wright arcs and give complete stability when closed. Another important practical advantage is that the width of the inclinable ring has been reduced, permitting a smaller outside diameter. This not only makes the stage available for smaller microscopes, it results in a lower and more convenient distance between the horizontal axis and the microscope stage, and a shorter horizontal axis. The base of the present Fedorov stage no longer has projecting parts which cover the graduations of a standard 12 cm. microscope stage.

AN IMPROVED FEDOROV STAGE (THREE-AXIS).

The stage is illustrated in fig. 1, and the new details of construction will be understood from the drawing (fig. 2). Reference has already been made to the main features that have been introduced as a consequence of the limitation to three-axis design. In addition to these developments the authors have made several independent changes in order to give greater facility in handling the stage.

1. *Horizontal axis.*—The divided circle on the A_4 axis has been separated from the knurled operating head and placed at the left-hand end of the axis. The existence of a certain discomfort in the close adjustment of this axis has been evidenced by the very large size given to the knurled head in recent models which have no slow movement. A fine adjustment has therefore been provided, as in the early model by the Société Genevoise (Duparc and Pearce, p. 283).

2. *Central plate.*—The knurled heads that usually serve to fix the metal plate bearing the upper hemisphere have been transferred to the under side of the stage, and the rather unstable small springs in these heads have been replaced by a construction in which the upper hemisphere is rigidly supported by a detachable bridge, while the whole central surface of the stage rises upon springs so that the microsection is held in position against the upper hemisphere. The sprung central plate has the great advantage that a microsection can be readily moved about by gently pressing on the ends of the glass slip so as to relieve the

pressure between the upper hemisphere and the cover-glass, care being taken not to depress the slide so far as to draw air into the inter-space.

3. *Adjustment for thickness.*—Compensation for the thickness of the mounting-slip underneath the microsection, hitherto made by a shallow threaded vertical movement of the central plate, is now taken up automatically by the springs. Adjustment of the centre of the hemisphere to coincidence with the axes of rotation is made independently by rotating the threaded mount of the upper hemisphere by means of a special castellated ring on the mount which can be adjusted by the fingers from above without disturbing the normal position of the stage. The same movement also permits the interchange of hemispheres of different refractive index.

4. *Graduated net.*—Both for the selection of a suitable crystal under the microscope and for determining the thickness of a grain after optical measurement on the Fedorov stage, it is important to be able to re-locate the same grain on either instrument. For this purpose a network of $\frac{1}{2}$-cm. squares is engraved on the central plate of the Fedorov stage, and a similar net is engraved on a ring-plate which can be inserted in the stage of the microscope. The edges of the mounting-slip must be set parallel with the lines of the net. When the required grain is at the centre of the field, the co-ordinate position is read from the top and side edges of the slip (the top being identified by the writing on the label, or other distinguishing mark). To regain the same position the appropriate edges are again set to coincide with the recorded values on the grid. The numeration has been chosen so as to eliminate any possible confusion between the x and y co-ordinates or between the left- and right-hand ends of the slide. Sometimes the reading is conveniently taken at the left end, sometimes at the right, but the numbers themselves make it clear which end is being used. 0–5 belong to the right end, 9–13 to the left, and 14–19 to the top edge. If the 28×48 mm. slip is to be transferred to the Fedorov stage, the corners must not lie outside a circle of 7 cm. diameter.

5. *Area available on the microsection.* Existing four-axis stages apparently offer a fairly wide movement for the microsection, but they are in fact severely limited by the subsequent collision of the ends of the mounting-slip with projections such as the hinge-blocks of the axis A_2. For a 28×48 mm. slip the actual area of the microsection that is accessible without such collision in the case of a standard four-axis stage is defined by the outer curved lozenge shape in fig. 3 (p. 159). In the

present model the central space is free as far as the inner side of the outer tilting circle, and there are no isolated projections to cause a collision
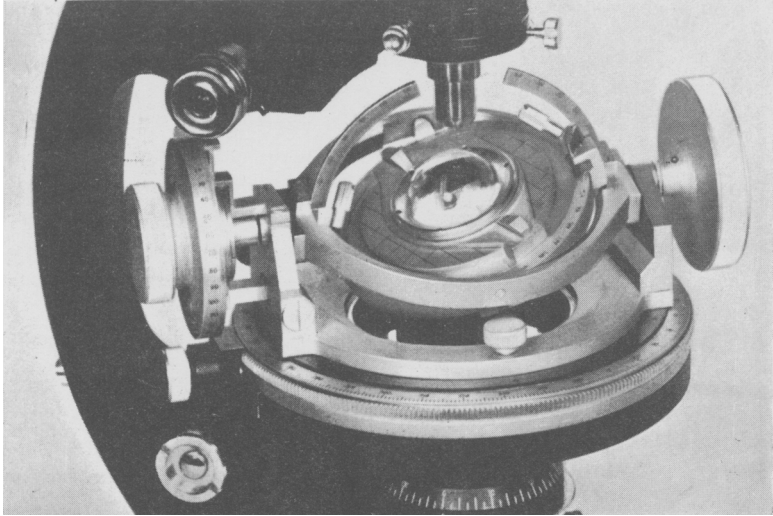

FIG. 1. Improved three-axis Fedorov stage, in place on a 12 cm. microscope stage.

Note. Clamp locking on the fixed Wright arcs; graduated net on the sprung central plate; adjustable upper hemisphere; slow-motion head to horizontal axis.

within this space. Consequently, in spite of the relatively small outer diameter, the radius of the free central space has only been diminished by $\frac{3}{4}$ mm. The actual area now available for the same mounting-slip is shown by the inner lozenge in fig. 3. A crystal that lies outside the available area can if need arises be reached in either case by cutting away the distant ends or corners of the mounting-slip. It may be noted that some firms are using slips of the size 27×46 mm. instead of the usual 28×48.

6. *To insert an object-slip.*—A_4 is locked at zero and the central part of the stage is fixed in an inclined position by means of the lock on one of the Wright arcs. A small amount of immersion liquid is placed on the middle of the upper and lower surfaces of the object-slip. The central plate of the stage is depressed by the left hand while the slip is inserted under the upper hemisphere.
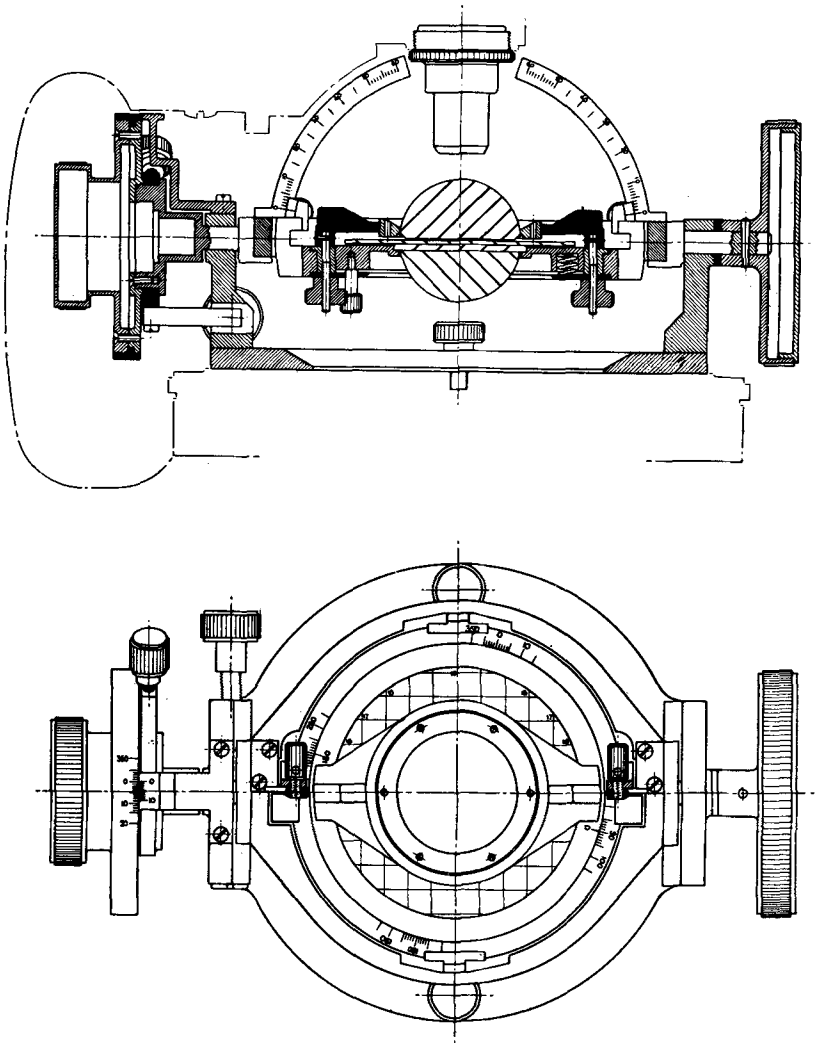
FIG. 2. Improved three-axis Fedorov stage (plan and section).

PRELIMINARY ADJUSTMENT AND CHECKING.

The above instrumental changes, and the introduction of new methods for hemisphere adjustment and in place of autocollimation, entail substantial changes in the text-book routine for adjustment. A brief outline of these will now be given. As will be seen, some parts of the old

procedure are still available. On the other hand, some new methods can be applied to the older types of stage.

In discussing the title of his work 'Mineralbestimmung' Berek (1924, preface, p. ix) pointed out that the universal stage should be regarded as an accurate means of determining minerals in general, as well as the less strongly birefringent felspars. For this reason it will be necessary to consider the adjustment of microscope and stage with greater care than would otherwise be needed.

Apart from the initial difficulty of exactly identifying and adjusting an optical symmetry plane, cleavage, &c., and the effect of difference in refractive index between crystal and hemisphere, the chief sources of error are: (1) in the microscope used, incomplete alinement of the optical axis and that of the stage; (2) imperfect centring of the upper hemisphere to the axes of rotation; and (3) small errors due to graphical methods. The errors inherent in the mechanical construction of the Fedorov stage itself are usually well within the limits required, but 'zero readings' may in some cases have to be ascertained for subtraction from the observed angles.

A. *The microscope stage and axis.*

It will be assumed that the polarizing system and cross-lines of the microscope are already in correct adjustment. Both for general convenience and for the accurate measurement of extinction with the biquartz and of path difference with the quartz wedge, a Dick-Wright ocular is to be preferred. On the smaller microscopes the objective should be attached directly under the hand-centring screws, in the place of the vertical illuminator (fig. 1).

1. *Axial alinement.*—Two methods have been proposed for verifying the alinement of a rotation axis, in this case that of the microscope stage, with the optical axis of the microscope. Of these, autocollimation has nearly always been employed, but the alternative, which may be termed the 'Nachet method', will here be preferred. For autocollimation some more or less elaborate arrangement is fitted, in which the image of a mark in the microscope is reflected by a glass surface parallel with the microscope stage. The coincidence of the mark with its reflected image indicates that the stage is normal to the axis. Sometimes only the image of a mark fixed on the mechanical axis is reflected on to the cross-lines in the eyepiece, the mark itself not being visible. Illumination is often difficult, and autocollimation may be said to be generally rather difficult and troublesome in practice.

2. *The Nachet method.*—This very interesting method, hitherto almost completely neglected, is described by Wülfing (Rosenbusch, 1922, p. 431) and is particularly suitable for the present purpose. It is based upon a construction used in the early Nachet microscope, and we have accordingly referred to it by this name. A slide of strewn dust or a fine ground glass is placed on the microscope stage. The objective is removed from the tube and is supported in a short tube of metal or paper at its usual working distance above the slide. Thus an image of the object is still formed in the eyepiece, but when the stage is rotated the objective rotates with it instead of being fixed to the tube. When the stage is turned, the image in the eyepiece rotates about a point which marks the intersection of the mechanical axis of rotation of the stage with the focal plane of the eyepiece. It is easy to verify that the position of this point is in no way affected by the nature of the objective or its position (provided that it transmits light in the required direction) or by the flatness or quality of the object if of suitably fine grain. The apparent centre of rotation in the eyepiece is easily identified, and the degree of coincidence with the cross-lines can be checked, preferably with the eyepiece net micrometer (1 mm. squares). If the distance from the cross-lines to the stage is, say, 200 mm., a lack of coincidence of 1 mm. will represent an error of 17 minutes. In the ordinary use of the Fedorov stage this is probably a suitable upper limit, but closer agreement may be advantageous. If desired the correction may be measured and applied to the readings.

The objective may now be replaced on the microscope and centred in the usual way. When this has been done, the effective optical axis of the microscope is the line joining the centre of the stage to the cross-lines. No appreciable defect is caused because the objective is not perfectly coaxial within the present limits.

B. *Adjustment of the Fedorov stage and determination of zero readings.*

After removal of the ring-plate from the centre of the microscope stage, the Fedorov stage can be attached by two fixing-screws that engage with holes in the microscope stage. The knurled head of the main horizontal axis should be on the right-hand side and the microscope stage at zero.

1. *Centring* (usual method).—With the Fedorov stage at zero markings the microscope is focused on a slide, in theory without the upper hemisphere; the microscope stage is rotated and the centring of the objective is corrected if necessary, so that the centre of rotation of the

image coincides with the cross-lines. The microscope stage is then locked and the innermost circle A_1 of the Fedorov stage is rotated. If the centre now obtained does not coincide with the cross-lines the fixing-screws must be somewhat loosened while the Fedorov stage is moved till correct centring is obtained. In practice the hemisphere may be in place.

2. *Axial adjustment.* (Nachet method).—Lock the Fedorov stage at the zero markings and place the objective in the short tube on a ground-glass slip as described above, or in a special tube fitting above the hemi-sphere. On rotating the innermost circle A_1, the point of intersection of its axis with the focal plane of the eyepiece can be identified. It should coincide with that of the microscope stage axis, which can be at once re-located by rotating the microscope stage. As in the case of the micro-scope stage axis, a difference of 1 mm. represents about $\frac{1}{4}$ degree. If the error seems important for the class of work that is being undertaken, bring the two centres into coincidence by slightly inclining the section about the axes A_2 and A_4. Lock these axes and read the values, which are the zero readings for the respective divided circles, and are to be subtracted from the observed angles. For this purpose coincidence should be obtained with the microscope stage axis, not the cross-lines, for which the error has already been estimated (para. A 2 above).

N.B. The Nachet method is sensitive to centring as well as to the inclination of the axis, and operation (1) above must always be completed before the Nachet method is used.

3. *Zero reading for the microscope stage* (Berek, 1924, p. 36).—Place the upper hemisphere in position and focus the microscope on specks of dust, &c., on the upper surface of the hemisphere. When the horizontal axis A_4 is turned, the image of the dust should traverse the field parallel with the N.–S. cross-line. To bring a dust particle nearer to the cross-line, incline the hemisphere a little about the A_2 axis. Dark ground or top lighting may be helpful. If the movement is not parallel with the cross-line, rotate the microscope stage till this adjustment is obtained. The angle then read on the stage vernier is to be subtracted as a zero reading from the readings for any rotation that may be measured on the micro-scope stage.

4. *Verification of the intersection of the tilting axes A_2 and A_4* (usual method).—Focus the microscope through the upper hemisphere on a microsection *with normal thickness of cover* (see (5) below). Rotate about the horizontal axis A_4 and note whether the points in the image appear to move across the field. If they do so, adjust the height of the hemi-sphere by turning the threaded mount which has been provided with

castellations for this purpose. When the movement has been elimi-
nated, the edges of the field will go out of focus as A_4 is inclined, but a
band parallel with the A_4 axis will remain stationary and in focus. This
should cross the centre of the microscope field. Similarly, without
further adjustment, when A_4 is at zero, a band at right angles to the
first can be identified by inclining the section about A_2. If the image
does not remain nearly steady when the second axis A_2 is turned, the
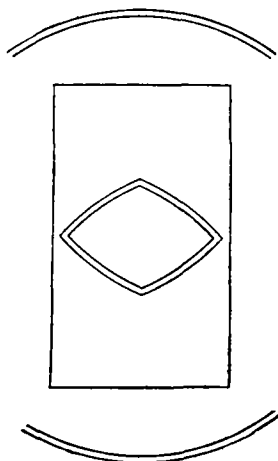second axis is either above or below the first. This condition is rarely

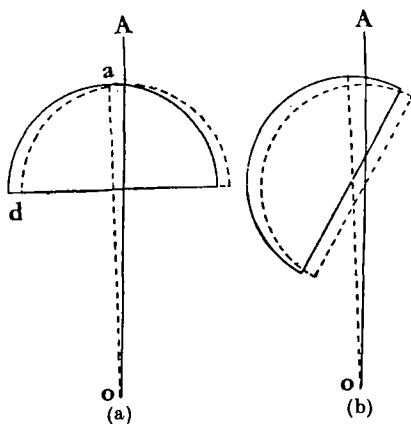FIG. 3.   FIG. 4.

FIG. 3. Centre of Fedorov stage.
FIG. 4. Deviation of axial line in a displaced hemisphere.

found. If present, it can only be remedied by returning the stage to the
factory. A new and more sensitive method is given below (5).

5. *Centration of the upper hemisphere.*—Little or nothing has been said
in most text-books about the refractive effect of the glass–air surface of
the hemisphere. *Principle involved*: Let A (fig. 4a) be the optical axis
of the tube and objective and Fedorov stage when in proper adjustment.
The centre of the hemisphere when correctly adjusted should lie on this
line. Suppose the hemisphere is displaced laterally by a distance d. The
direction A now undergoes refraction on entering the hemisphere and
converges upon o, the principal focus of the upper surface. The distance
ao may be taken as approximately three times the radius of the hemi-
sphere. For a hemisphere of radius 12 mm. a lateral displacement d equal
to 1 mm. will therefore cause a deviation of $\frac{1}{36}$ radian $= 1.6$ degrees.

If a maximum tolerance of $\frac{1}{4}$ degree is accepted, the hemisphere must be centred within 0·17 mm.

The effect of displacing the hemisphere in this way may be demonstrated as follows. With a little oil attach a microsection to the central glass plate and centre the microscope and Fedorov stage as usual. With the stage locked at zero place one of the loose (under) hemispheres upon the microsection, with enough oil to enable it to slide about freely without disturbing the object. When the previous centration is again checked it will be found that the centres of rotation have not been displaced by the presence of the hemisphere, even if it is badly off centre. This is an example of the Nachet principle already described. As the hemisphere is displaced, however, the image moves across the field. Only when the hemisphere is truly centred will the point imaged on the cross-lines be the same as that seen without the hemisphere.

Test for central mounting.—It follows that displacement of the hemisphere could pass completely unnoticed during the ordinary tests by rotation. The mounting of the hemisphere does not usually cause any noteworthy error. It may be checked by centring an isolated particle on the cross-lines as above and then placing the upper hemisphere in position. The image of the particle should still be found on the cross-lines, within the tolerance allowed. For an error of $\frac{1}{4}$ degree this will be an apparent distance $\frac{2}{3}d$ on the object, 0·11 mm. The error is best measured by inserting a micrometer net in the eyepiece. With a $\times 5$ objective ($\times 7\cdot5$ with hemisphere) one may say that the image must not be displaced by more than 0·7 mm. in the focal plane of the eyepiece.

The objective stop.—In the conoscopic system (if the Bertrand lens is used with the cross-lines for the present purpose it must be in accurate adjustment with the optical axis already established) the back of the 0·15 N.A. objective includes a conoscopic angle of about 17 degrees *inside* the hemisphere. A circular stop one-tenth of the objective diameter will include $\pm0\cdot8°$. If a small light-source is imaged without the stop through the loose hemisphere, the change of direction due to displacement of the hemisphere can be demonstrated by the movement of the spot of light at the back of the objective. Seen in this way the effect does not seem very large, but such displacements are comparable with the accuracy of adjustment attainable for a narrow zero isogyre or for a favourable extinction setting in the orthoscopic system. For accurate results, the use of the small stop seems inevitable; it may conveniently be directly centred to the back of the objective, and is preferably an iris.

Vertical adjustment of the hemisphere.—No universal stage has so far

been provided with means for altering the distance between the micro-section and the hemisphere: the two move together. The hemisphere is really a segment with an allowance (0·007 inch) for the thickness of cover-glass and balsam above the section. If the thickness of cover differs from this value, the section when adjusted in the axis of rotation will not contain the centre of the hemisphere, which will be too high or too low. Since, however, the tolerance as above (see fig. 4b) will be about 0·17 mm., serious error can only arise when the microsection is too low, i.e. when the cover is too thick. When the adjustment of height is made in the usual way (para. 4 above), the position at which the object appears to be stationary is really a compromise between the effects of two displacements, of the hemisphere centre and of the microsection. The usual method is only valid if the cover is of standard thickness.

In the present design the hemisphere is independently supported by the bridge, and if it has been adjusted to coincide with the rotation axes (by using a correctly covered section or as below), the microsections should be interchangeable without readjusting the hemisphere for height. In this case any different thickness of cover will be evidenced at once by the displacement of the image on rotating about A_2 or A_4. If exces-sive it is best eliminated by re-covering the microsection with a suitable cover-glass. Although small movements of the image may cause incon-venience, a low position of the microsection is not in itself a cause of error, since angles alone are in question. It would seem that for the most accurate measurements the hemisphere should be kept fixed in the bridge at the proper height, at which its centre coincides with the inter-section of the stage axes.

A very accurate direct test of the height of the hemisphere can be made as follows. An objective of shallow focus, say 4 mm., is focused on the surface of the hemisphere. Readings for the position of the surface are made on the micrometer fine-focusing screw. On inclining the hemi-sphere about the axis A_4 or A_2, the reading for the zero position should be midway between those for the greatest inclination on either side. If not, the microscope micrometer can be set to the desired reading and the hemisphere (at zero) raised or lowered in the screw-mount to the correct level. The test is very sensitive, and a difference of about 0·1 mm. is permissible between the inclined readings. This difference is a test of the centring of the hemisphere horizontally on the axes A_2 and A_4. When the height is correct the height-curves are centro-symmetrical and nearly linear.

6. *Other verifications.*—Several other tests are well known or will

suggest themselves; they need not be discussed in detail since the results rarely reveal any error. Thus, after (3) the angle of 90 degrees between the cross-lines can be checked by rotating the microscope stage through 90 degrees and moving the dust particle parallel with the other cross-line. Again, in the same way, by inclining first about A_4 and then about A_2, it can be verified that these two axes are at right angles to one another.

The tests in the last three sections (4 to 6) will not need to be repeated for the same instrument unless the hemisphere has been disturbed, but it will always be advisable to carry out the first three checks as a preliminary to making a series of measurements, in case the Fedorov stage has been displaced. The authors believe that, owing to the introduction of the Nachet method, it has now become possible to make a complete zero check with great facility and accuracy. During use the centration of the image should be checked occasionally by rotating the microscope stage, to make sure that the centring of the objective has not been disturbed. A section with correct thickness of cover may be kept for adjusting the height of the hemisphere.

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Postscript.—In figs. 1 and 2 the hemisphere mount has been since replaced by a castellated ring operated by the fingers, which does not cause the hemisphere to rotate during adjustment.