# THE USE OF COLLIMATORS FOR TESTING AND ADJUSTING INSTRUMENTS*

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THERE is an old saying, "A poor workman blames his tools," but it might also be said that no matter how proficient the workman, the results of his labours will depend to a certain extent upon the equipment he uses. For the engineer engaged upon work of high precision, modern science has created masterpieces of mechanical skill. The surveyor can now measure angles with an instrument which reads by estimation to a tenth of a second of arc and which is so finely fitted that the tolerance between certain moving parts is only a few ten-thousandths of an inch. The instrument maker has done his part, but in order that the equipment may function with maximum efficiency it is essential that it be kept in perfect condition and subject to frequent tests. For this purpose, field methods are frequently inadequate. They have been superseded by the laboratory equipment where, working under ideal conditions, it is possible to detect the smallest inaccuracy, diagnose the particular trouble, and make those fine adjustments which alone assure perfect operation.

Canada's need for a workshop of this nature was realized many years ago, but it was not until 1911 that the late Dr. E. E. Deville succeeded in having one built. The Doctor, who at that time was Surveyor General of Dominion Lands, demanded accurate work from his surveyors, but he knew that to obtain that result they must be supplied with instrumental equipment of precision. A special building was erected for the sole purpose of testing and adjusting instruments, and his wisdom and foresight have been amply proved by the ever increasing demands made by Departments of Government for various laboratory checks. To-day, in the National Research Building, Canada can boast of a department which was specially equipped for the handling of all such problems.

For the general testing of theodolites, the equipment is fairly simple, consisting in the main of a required number of collimators mounted on piers placed on the semi-circumference of a circle, of which the pier supporting the instrument to be tested forms the centre. A spacing which proved very satisfactory consisted of having two collimators 180° apart, and a third 60° from one of them. For further tests, a vertical collimator or one at an angle of 45° above the horizontal plane may be used to advantage.

The laboratory in which this equipment is used must, however, meet certain very definite requirements. It should be so located that the temperature will be almost constant and not subject to sudden changes. Supports for both collimators and instrument should be of solid construction with the foundations on bedrock. The collimator room used by the Canadian Geodetic Service is situated in the sub-basement, the collimators and instrument are supported on concrete pillars free from the walls, the daily temperature range is less than 2°, and the angular spacing of the collimators does not change by more than 2 seconds per week. The necessity of these precautions can easily be seen when it is realized that in making laboratory tests all external causes of trouble must be eliminated as far as possible, and the records obtained should give a true picture of the operation of the instrument.

As to the collimators themselves, although telescopes designed particularly

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for collimator service have certain advantages, any theodolite or level with a good telescope can be adapted for the purpose. Excellent results have been obtained in Canada by using old style 12-inch theodolites, the whole assembly being mounted on the pier.

The illumination and definition of the collimator cross-hairs is very important. Satisfactory results may be obtained by removing the eyepiece and substituting a small cylinder with an aperture of 1/50 inch diameter, adjustable longitudinally with reference to the collimator axis. Ground glass and a green filter in front of the light source provide an even illumination which is easy on the eyes. Sharpness of definition may be produced by masking the objective to as small an aperture as possible consistent with clear illumination of the wires (about $1\frac{1}{2}$ inches). The size of the aperture in the mask and distance from the light source are determined by trial and error.

The accuracy of the setting and adjusting of the collimators depends entirely upon the nature of the test which is to be performed. For many minor purposes, the exact alignment of the collimators and their precise adjustment to infinite focus are not essential, but for other tests these adjustments must be performed most meticulously. Particularly is this the case where changing eccentricity of the test instrument is a factor. This may occur where the base of the theodolite is rotated during a test or where a comparison of the measured value of an angle with different instruments is required. To give an idea of the effect of maladjustment of focus on angular values, an extreme case may be cited in which the angular value between two collimators changed six seconds for successive movements of 0.1 inch in the eccentricity of the theodolite.

With the collimators and instrument to be tested in their approximate positions, all optical axes should lie in the same horizontal plane and at a height which would be convenient for the average observer. This elevation may be determined with a precise level. As instruments vary in size, the support of the centre theodolite should, if possible, be adjustable for height.

The next task is the aligning of collimators on the test instrument. For the two collimators 180° apart, fine weighted threads are suspended over the centre of both eyepiece and objective, and with the two instruments pointed on one another, the respective alidades are rotated—and moved horizontally if necessary—until the four threads are in line, the two collimators still pointed on one another. The centre for the instrument to be tested was found by a plumbob intersection with this line. The third collimator may be lined in with threads in a similar manner, only in this case, the test instrument—with plumbob over its centre—is sighted on.

To adjust the collimators to infinite focus, various methods may be employed. That utilized by one instrument maker is to focus two collimators on each other, then focus a third on one of them and finally test the focus of this third collimator on the first. As the focus of collimators is complementary, if the first were focused for near vision, the second will have been adjusted for far vision and the third for near vision. The third and first then cannot be in focus one with the other since both are focused for near vision. By successive approximations with pairs of collimators, the three can eventually be adjusted to infinite focus and will then be in exact focus with each other.

The method employed by the Geodetic Service may be called the eccentricity test and does not involve disturbing the position of any of the collimators. A precision theodolite is mounted on the central pier after being set as close as possible to infinite focus out-of-doors. Two collimators are then brought meticulously into focus with this theodolite by adjusting their focusing screws. Any error of focus of these collimators is hence the same and is opposite to that of the central theodolite.

The central theodolite is now moved successively half an inch along the bisector of the angle between the two collimators—towards and away from the collimators—and the angle between the collimators measured in the two positions of the theodolite. If these angles differ—and they usually do—the central theodolite and the collimators are not at infinite focus. By a system of trial and error, the Geodetic Service has evolved a method of adjusting the focus of the two collimators and the central theodolite so that the above two measurements of the angle—representing a total eccentricity of 1 inch—will not vary by more than 1 second from one another.

With the completion of these preparations it is fairly safe to assume that any instrumental tests will be unaffected by errors due to atmospheric or temperature changes, or indefinite targets.

To illustrate one recent use of collimators for the testing and adjusting of theodolites I will confine myself to certain tests which were conducted by the Geodetic Service of Canada. Some years ago we purchased a new type of precise theodolite which had a number of advantages over the 12-inch instruments then in use. It was light in weight, easy to read the circles, and speedier in operation. But it embodied in the axes design a radical change from most other models. After three years of successful field operations, angular measurements failed to reach that high standard so necessary for primary triangulation, and it was decided to conduct exhaustive tests to determine definitely whether the trouble was due to external influences or purely instrumental. Field tests were not necessarily conclusive; there was always the possibility that atmospheric conditions and the varying definitions of the targets might be contributory causes to the results obtained.

Not knowing what to look for made it extremely difficult to devise a definite program. In the laboratory, comparisons were made with the older types of theodolites in the measurement of angles between collimators. In some cases the results indicated equal accuracy; in others, although the new type of instrument gave consistent values for the same angle, it was not the same as that read by the older theodolites. Finally it was discovered that the position of the base with relation to the alidade had a definite bearing on the measurement of the angle read, and after investigation, it was concluded that the cylindrical steel vertical and horizontal axes, though appearing to work freely, really did not fit. This lack of fit produced changing strain in the metal as the vertical axis was revolved, which, being transferred through the standards and telescope, produced varying deflections of the collimator axis at different azimuths and caused angular errors of as much as 3 or 4 seconds. It was also found that the cylindrical telescope axis in its close fitting bearing contributed to the trouble. In other words, each change in the relation between the male and female axes produced a change in the deflection of the line of collimation.

The cause of the trouble was due to slight warping of the hardened steel axes following manufacture.

Before describing the test which was devised to reveal the existence of axis strain, it is interesting to see how this condition explained certain field experiences. It must be realized that, so long as the base of the theodolite remains stationary, the errors due to axis strain will be constant for any direction, and hence the strained theodolite will deliver as fine appearing a set of directions as one with unstrained axes. In the field, particularly if the station was difficult of access, the observer would stay an extra night in order to check his results.

On the second night he would mount the theodolite in the same position as the previous night to avoid relevelling, and of course would get a confirmation of his original readings. If it became necessary to reoccupy the station at a later date, the results would very likely be quite different because of the different setup of the theodolite base. In a particular case where a tower was necessary in order to see all points, the observer decided to take another set from the ground on those points which were visible from that altitude. The two sets of directions appeared equally good, but were considerably different. Again, the change in the position of the footscrews provided the explanation. A number of other puzzling circumstances which could have been caused by atmospheric conditions—if they had existed at the time—were explained by the axis strain theory.

With this information, it was comparatively simple to devise a program which would definitely prove or disprove the theory. Before being placed on the pier, the instruments were first cleaned and oiled, optical parts examined, moving parts tested for freedom of movement and the footscrews tightened to a snug fit. With the collimators adjusted for infinite focus, the instrument telescope was centred and then focused on one of them.

The strain test consists of taking six sets of measurements of an angle of 60°. Each set is made up of six positions, direct and reverse, using definite settings for the horizontal circle and with a definite relation between the base and the alidade. For example—for position 1, set No. 1, the base of the instrument is set on a graduated plate and a marked footscrew rested in a slot marked "zero." The telescope is sighted on "A" collimator with the horizontal circle set at zero. Commencing in a clockwise direction the angle between A and B is read and the circle closed on A, followed by an anticlockwise swing after the telescope has been transited. The value of the angle is calculated from the mean of the two. Two more positions are then taken, the only change being that the circle settings are changed, being increased by 60° each position. This completes the first half of set No. 1, and provided there is no strain, any difference between the three angles will be due to graduation errors plus very small pointing and reading errors. For set No. 2, the base is rotated 60° in an anticlockwise direction, the horizontal circle set at zero and the procedure is the same as for No. 1. Three angles are read with the circle settings as before. By successive rotations of the base between each half set, we finish the first half of the test with the marked footscrew at the 300 degree mark. For the second half, with the base set at 300°, the horizontal circle is set at 180°, 240° and 300° and the angle between "A" and "B" read as before, the three readings being grouped with those taken with the same position of the base. After each half set the base is rotated 60°, this time in a clockwise direction, until at the last half set the base is back at zero.

I would draw your attention to Table I which shows a résumé of a test on an instrument with strained axes, together with a test of the same instrument after the axes had been remodelled to remove the strain.

An examination of Table II will show the calculation of the strain error from the tests described in Table I. The average strain error which is considered permissible has been set at 0.12″. With strained axes, the theodolite in question showed an average strain error of 0.75″, while the same instrument after the strain was removed showed this error reduced to 0.04″.

It might be noted that the above test, besides strain, reveals many other troubles—should they exist—and for that reason is exceedingly valuable for the checking of all precision theodolites both before and after field use.

TABLE I. TESTS FOR AXIS STRAIN IN THEODOLITE WITH AND WITHOUT STRAINED AXES

| Theod. Base | Sequence of Readings | Circle Setting | With Strained Axes: Collimator A | With Strained Axes: Collimator B | With Strain Removed: Collimator A | With Strain Removed: Collimator B |
|---|---|---|---|---|---|---|
| 0 | | 0° | 0°00′00.0″ | 60°00′02.7″ | 0°00′00.0″ | 59°59′56.6″ |
| | 1 | 60 | | 03.6 | | 57.3 |
| | | 120 | | 04.7 | | 57.6 |
| | | 180 | | 01.5 | | 55.4 |
| | 12 | 240 | | 03.4 | | 56.7 |
| | | 300 | | 03.6 | | 57.6 |
| | | | | Mean 03.25″ | | 56.87″ |
| − 60 | | 0 | | 02.1 | | 56.4 |
| | 2 | 60 | | 03.3 | | 56.5 |
| | | 120 | | 03.7 | | 57.6 |
| | | 180 | | 01.7 | | 55.4 |
| | 11 | 240 | | 01.6 | | 56.3 |
| | | 300 | | 04.1 | | 57.7 |
| | | | | Mean 02.75″ | | 56.65″ |
| −120 | | 0 | | 57.5 | | 56.0 |
| | 3 | 60 | | 00.8 | | 56.8 |
| | | 120 | | 00.3 | | 58.0 |
| | | 180 | | 00.0 | | 55.6 |
| | 10 | 240 | | 59.4 | | 56.1 |
| | | 300 | | 02.2 | | 57.6 |
| | | | | Mean 00.03″ | | 56.69″ |
| −180 | | 0 | | 01.6 | | 56.5 |
| | 4 | 60 | | 02.6 | | 57.2 |
| | | 120 | | 03.8 | | 57.5 |
| | | 180 | | 02.7 | | 55.6 |
| | 9 | 240 | | 02.4 | | 56.8 |
| | | 300 | | 04.6 | | 57.6 |
| | | | | Mean 02.94″ | | 56.87″ |
| −240 | | 0 | | 01.9 | | 56.1 |
| | 5 | 60 | | 02.9 | | 57.1 |
| | | 120 | | 04.4 | | 57.4 |
| | | 180 | | 03.2 | | 55.8 |
| | 8 | 240 | | 03.8 | | 56.6 |
| | | 300 | | 05.0 | | 57.6 |
| | | | | Mean 03.53″ | | 56.77″ |
| −300 | | 0 | | 01.4 | | 56.2 |
| | 6 | 60 | | 00.7 | | 57.1 |
| | | 120 | | 02.9 | | 57.7 |
| | | 180 | | 59.0 | | 55.8 |
| | 7 | 240 | | 00.7 | | 56.5 |
| | | 300 | | 00.6 | | 57.4 |
| | | | | Mean 00.88″ | | 56.78″ |

TABLE II. CALCULATION OF DIAMETRAL STRAIN ERRORS FROM TESTS OF TABLE I

*Theodolite with Strained Axes*

| Theodolite Base | Angle | Residual | $r$ | Diametral Strain Error |
|---|---|---|---|---|
| | 60°00′ | | | |
| 0° | 03.25″ | 1.02″ | 1.02″ | −0.55″ |
| 60 | 02.75 | 0.52 | 1.54 | 0.47 |
| 120 | 00.03 | −2.20 | −0.66 | 0.99 |
| 180 | 02.94 | 0.71 | 0.05 | −1.21 |
| 240 | 03.53 | 1.30 | 1.35 | −0.50 |
| 300 | 00.88 | −1.35 | 0.00 | 0.80 |
| | Mean 02.23″ | | $\Sigma r=3.30''$ $\frac{\Sigma r}{6}=0.55''=C$ | Arith. mean 0.75″ |

*Same Theodolite with Unstrained Axes*

| Theodolite Base | Angle | Residual | $r$ | Diametral Strain Error |
|---|---|---|---|---|
| | 59°59′ | | | |
| 0 | 56.87″ | 0.10″ | 0.10″ | 0.00″ |
| − 60 | 56.65 | −0.12 | −0.02 | 0.10 |
| −120 | 56.69 | −0.08 | −0.10 | −0.02 |
| −180 | 56.87 | 0.10 | 0.00 | −0.10 |
| −240 | 56.77 | 0.00 | 0.00 | 0.00 |
| −300 | 56.78 | 0.01 | 0.01 | 0.00 |
| | Mean 56.77″ | | $\Sigma r=-0.01''$ $\frac{\Sigma r}{6}=0$ | Arith. mean 0.04″ |

The method of removing axis strain consisted of a change in the design, reducing the width of the cylindrical bearing surfaces and the substitution of an entirely different type of ball race. The reduction of residual telescope axis strain alone presented a particular problem, but the employment of kinematic design as exemplified in the Y bearings gave the best results. A modified form of this bearing proved very satisfactory with a certain type of theodolite having cylindrical telescope bearings.

Earlier in this paper I mentioned that a collimator placed in the laboratory at an angle of 45° above the plane of the theodolite might be used to advantage. In ordinary surveying, the observations are mainly taken within 2° or 3° of the horizontal plane, but there are occasions in particularly rough terrain when these values are greatly exceeded. Unfortunately all theodolites are not equipped with a stride level and hence it may be impossible to check the horizontality of the telescope axis and make the necessary reductions. Errors of considerable magnitude may be introduced when readings are taken from points of varying altitude. In the laboratory, it is possible to calculate this lack of horizontality in the telescope axis and adjust it by trial and error. The angle between the 45° collimator and one in the horizontal plane is read, direct and reverse, and the collimation computed from that on the horizontal. By substitution in the formula, $b \tan h =$ Correction to horizontal circle reading—$c \sec h$; where $h$ is

45°; the correction to the horizontal circle reading is the difference between either reading on the 45 degree collimator and the mean of the direct and reverse readings; and $c$ is the collimation on the horizontal collimator; the value for $b$ will be the lack of horizontality in seconds.

It would be impossible to describe the many uses which are being made of the collimator in the laboratory for the adjusting and testing of precision instruments of which optics are an integral part. In the test which I have mentioned, we were confronted with an unknown which field tests failed to solve. Thanks to the collimator, we were enabled to determine definitely the source of the trouble, and with that information take the necessary steps to remove it. That our conclusions were accepted by the instrument makers themselves is sufficient proof that our diagnosis was correct.

I would like here to pay tribute to J. L. Rannie, who originated and supervised these tests, to W. M. Dennis who acted as chief diagnostician and suggested the cure, and to R. H. Field who was frequently called into consultation.

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A detailed description of the various tests carried out may be secured from the Dominion Geodesist, Geodetic Service of Canada, Ottawa.