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It is a fact familiar to those who have occasion to make use of instrumental contrivances, that novel methods are constantly being devised to meet new requirements or to lessen existing defects. As the delicacy and importance of any given work is increased, the observer soon discovers sources of error that had not been suspected, and finds errors that were veiled by the disposition of the relative parts of the instruments. Instruments of the higher class are too frequently at fault, but the ingenious observer is soon led to investigate the sources of trouble, and either to obviate them or to seek for the best instruments suited to his particular and peculiar duties. In the broadest view of the case we must not be confined to individuals or to nationalities, but aim only to obtain the highest mechanical design and workmanship. In the progress of the geodetic work of the United States, stretching from the Pacific to the Atlantic, and also northward and southward along the Pacific coast, there was furnished to me, among other instruments, one theodolite, of large size, which was subjected to the most rigid scrutiny to determine the flexure of the pillar plate, of the microscope arms, and of the telescope; also, the character of the graduation of the 20-inch circle, and various other points involving accuracy. Under ordinary circumstances the instrument would have passed muster for lines of moderate extent, but when lines of 160 miles in length were involved, it was essential to the integrity of the undertaking, that errors of even a second of arc should be avoided. At the distance of 160 miles one second of arc subtends four feet; a skilled observer can measure a much less quantity than one second, and certainly the instrument should afford the means of his measuring what he can see.

Fully alive to the importance of the subject, the Superintendent of the U. S. Coast Survey had determined that there should be made a careful examination and study of the instruments of precision, exhibited at the Paris exhibition for geodetic and astronomical work, topography and hydrography, for the telegraphic determination of longitude, etc. And, moreover, that the examination should be extended to the first-class workshops of Europe, where instruments of this character are manufactured.

It was desired to ascertain, if practical, whether the productions of European manufacturers were superior to our own; wherein lay any superiority, if found to exist; and in what consisted the peculiar merit of the work of any particular manufacturer.

As a mechanician seeking merely the trade secrets of the makers, I could not have expected to enter into any sanctum sanctorum; but upon a candid explanation of my purpose and instructions, I found nearly every workshop

opened to me, and full and free explanations made to my inquiries. It would therefore be unjust to these manufacturers to severely criticise in public the character or even the minor defects of their instruments, or to make known the methods of their processes. These I received for the benefit of the Government, and whenever I mention any names here, it will be to commend their work; although many are officially commended that are not now referred to.

In previous experiments upon the larger and finer instruments, I have discovered errors of graduation and flexure of parts much greater than I had any reason to suspect; and I believe much greater and more serious than the makers had thought possible. This latter is the more readily understood when we reflect how few mechanicians are actually observers; and that it really requires long practice for the most skilled observer combined with fair mechanical instincts to discover and measure the minute and conflicting errors which are resultants of different infinitesimal, and perhaps unsuspected causes. As a rule, the observer makes his measures upon objects subject to many extraneous and disturbing causes, and whenever unsatisfactory results are obtained, he is very apt to attribute them to the unfavorable conditions of the atmosphere or to his own condition and temperament at the time; generally overlooking the fact that the instrument maker was quite as liable as himself to errors of judgment in the proportions and workmanship of the instrument used.

Setting aside for the present the peculiar adaptness and fitness of the observer for his business, we are necessarily interested in the requirements of geodetic operations and especially in the duties of the instruments by which these are satisfied. In all geodetic work, portability, accuracy and maintenance of instrumental adjustment are essential to rapidity of progress, to economy of expenditure in money and in personnel, and to precision in the results. Experience and theory teach us that in any given instrument, such as a theodolite for geodetic purposes, we need simplicity of design; fewness of pieces; harmony in the proportion of parts; accuracy of workmanship; superior graduation with adequate microscope micrometers; micrometer screws free from mechanical defects; commensurate optical conditions of penetration and power; sensitive and trustworthy levels; and the highest precision in all the bearings of the moving parts. Moreover, the general disposition of the parts should be such as to offer the greatest facilities to the observer, in order that he may make the necessary observations without fatigue or nervous strain.

Guided by these general considerations, I examined the fine collection of geodetic instruments exhibited by the Minister of War, many of the exhibits of private exposants, and some of the workshops of the manufacturers in Paris. After this I visited the principal manufactories of Geneva, Neuchatel, Munich, Vienna, Dresden, Berlin, Hamburg, Cassel, London and York. At the exposition I did not have the fullest facilities afforded me, and not only was I unable to get into one of the principal cases, but I was positively forbidden to continue my drawings; whilst one well known maker would not only not permit me to make any tests of the graduation of his theodolite, but would not allow me see his graduating engine. Outside of Paris I was permitted to see every graduating engine of the noted manufacturers, and afforded facilities for the examinations of their productions. But on account of the commercial depression which was overshadowing all business in Europe, as well as the United States, the number of the larger instruments on hand was very few. In some workshops I found that not over 20 per cent. of the usual number of workmen were employed.

Besides the mechanical construction of the instruments, I was particularly anxious to study the capacities of the different graduating engines, in order to judge, in a measure, of the probable value of the results. The graduating engine is simply a mechanical tool with which we should expect to divide a circle of say 20 inches in diameter in 360 parts, with no greater an error than the 1-50,000 part of an inch or 4-10 of a second of arc in any one degree. The probable error of an experienced observer in reading the five minute graduations of such an instrument is about 1-10 of a second of arc, or the 1-200,000 of an inch. It is usually assumed that the graduation errors are not over one

second of arc, and this is what the majority of instrument makers suppose or assert to be their average error in each degree graduation; but I am perfectly satisfied that even this limit of accuracy is rarely if ever reached. As a matter of fact I failed to learn from any manufacturer that he had ever tested a theodolite after graduation by measuring every five minute space on the circle, or even every degree; whereas in my previous testings of a 20-inch theodolite I had detected differences of 15 seconds between whole degrees, and errors of 5, 6 and 7 seconds in contiguous five minute spaces.

You can readily understand the almost multitudinous sources of error against perfecting a graduating engine; and the most skilled mechanicians find that it requires persistent labor and experiment for two, three or more years to approximately effect their purpose. Yet until we get a reliable graduation it is futile to seek for final accuracy in our measures; nevertheless all other sources of error should be reduced to minima, and the perfection of graduation persistently attempted. After a graduating machine has been made as nearly perfect as the means and skill of the mechanician can effect it, he carefully measures the different degrees, tabulates the errors, and generally constructs an error circle whose circumference is irregular in a certain proportion to the errors determined. This circumference is so connected with the tangent screw moving the graduate circle as to advance or retard the screw the exact amount of the error at any given point. This is one way of effecting the necessary correction, and is mentioned merely to serve as an illustration; yet in this method it must be evident that the retarding of a screw brings into operation any backlash that may exist even if it be almost practically infinitesimal.

Among the instrument makers I found the most positive and opposite views of practice; for instance, one believes wholly in automatic moving parts in the graduating engine, and makes every effort to secure uniformity of temperature, etc.; another scouts the automatic movement and does everything by hand, with or without much attention to change of temperature; one party believes in a steel cutting tool; another pins his faith upon his diamond cutter, etc. Many of the observers implicitly receive the dicta of the instrument makers, and but few make any exhaustive examinations for themselves. Among the tests which had been made by the Chief of the Prussian Geodetic Survey, between theodolites of a few of the best makers, there was a very close agreement in the probable error of the systematic errors, but the probable error of the irregular errors was only half as great for the Wanschaff circles as for the others. Without here mentioning the names, I may state that from the character of the instruments examined, I recommended the Superintendent of the Coast Survey to have circles graduated by five of the best makers, and test them as I had tested the 20-inch theodolite referred to. For where mechanical skill is good and apparently nearly equal, it would be vain to attempt to decide by simple inspection or upon a maker's reputation, although upon these merits alone awards were made at the exposition.

After the instrument maker has effected the division of the graduating circle into degrees, the sub-division into 2-minute, 4-minute, 5-minute, or 10-minute spaces is sometimes made by verniers suitably divided, but frequently the coincidence of the lines of the vernier and the circle is determined by bringing the ends of the lines together, and judging by the eye whether one is truly a prolongation of the other. The Repsolds certainly appreciated this source of error and had in a great measure successfully overcome it. Some of the graduating engines examined had been made and in use from thirty even to fifty years; now considering the great advance in the construction of instruments of precision in that time, it is hardly too much to ask that this special mechanical tool should be perfected. Of course there are more recent efforts but not yet notably perfected. It offers to our younger skilled mechanicians a very delicate problem upon which to try their ingenuity, skill and patience; with such a tool superior to those of their competitors, they may be assured of a fair income from its work alone, and an enviable reputation.

Of the larger theodolites which I had an opportunity of examining, the best was by Brunner. It combined fewness and simplicity of parts, and fair

harmony of proportion, yet I should certainly doubt the adequacy of its optical power for long lines; it reads by four verniers instead of three, involving more labor, and less reading points on the circle; whilst the observer must be placed in a constrained position because the horizontal plane of the telescope is only about two inches above the reading microscopes. Moreover, the circle (instead of the whole instrument) is changed for new positions and clamped by three screws in each position. Should the surface planes of contact be warped, this clamping would warp the circle in each new position and thereby introduce error. This method was devised about 20 years since, and soon abandoned; it is now the fashion.

In the evident desire to obtain compactness and simplicity, the instrument is not adapted to the observing of azimuths by means of a close circumpolar star, because the telescope cannot be elevated. Instead, the transit instrument must replace the theodolite for that purpose, whereby the possibility of error is introduced in occupying the identical station; and even if this be granted, the labor is increased and extra time consumed.

Fashions prevail among instrument makers and observers just as we find a change of opinion upon the question of refractors and reflectors. At one time it seemed as if the prismatic telescope was to carry everything before it, and I find many manufacturers and observers yet strongly in favor of that form. It certainly has the decided advantage of comfort to the observer; but from personal experience, and from conferring with such observers as Plantamour, it seems that the system necessarily involves "flexure" or deformation of the prism, notwithstanding the numerous and ingenious efforts made to secure it properly in position. Of course some manufacturers insist that their special methods of securing the prisms are infallible; but the observer is the final judge of their failures. In the highest character of work I should certainly not use them; whilst for the secondary works it seems hardly necessary to increase the number and intricacy of the parts.

A prevailing fashion at present is to introduce reversing apparatus and counterpoises, even in theodolites with circles of eight inches in diameter. This is as complete a wandering from simplicity as can well be imagined, and must certainly lead to grave errors. It is well known that by moving a telescope in altitude by means of the usual slow-motion screw, the tendency is to raise the transit axis pivots, but as the weight of the telescope is too great to be lifted clear of the Y's, the pivot is moved up one side of the sloping Y, and the telescope thereby changed in azimuth. Now, if the weight of the telescope be counterpoised by springs, the pivot is lifted still higher and the resulting change in azimuth becomes greater. Not only that, but the intricacy of the adjustment thereby introduced, conflicts very much with the bearings of the vertical axis. I saw no form of reversing, that should be applied to any first-class theodolite, or to any theodolite which might be used at a distance from the workshop of a skilled mechanic. The same amount of labor otherwise expended upon the same instrument, would largely increase its value for honest work. This form, as well as the prism telescope, must however be demanded by observers or the makers would hardly continue their manufacture.

Another fashion that seems to prevail is the use of microscope micrometers upon small theodolites of eight inches diameter, and even in some cases of only six inches. These microscope micrometers read the circle to one or to two seconds; but in every such case the telescopic power and the transit axis level were vastly inferior to such delicacy, and therefore the contradiction existed that the instrument maker expected the observer to measure what he could not see. In fact, I think it may be safely asserted as a rule that the telescopic power of all the instruments examined was inferior to the other parts.

And still another fashion is in the use of the universal or Altazimuth instrument. The combination of two or more instruments for different purposes into one instrument for all the required purposes is difficult and doubtful even in machines of industry; but when every new piece and movement introduces a fresh source of error into a delicate instrument where the constant study should be really to decrease them, the combination must be clearly shown not

only to possess freedom from additional errors, but to give better results or as good results as two different and separate instruments at less cost of construction, less weight for transportation and mounting, and greater rapidity of manipulation. For certain classes of work, the universal instrument has, without doubt, some decided advantages; but for such work as is demanded in the primary and main triangulation of the United States they are essentially unsuited. Nor would our surveys willingly adopt the eccentrically placed telescopes of the theodolites used in the Prussian Geodetic Survey, although the character of that work stands very high; if any series of observation is broken it cannot be utilized without extra calculation; and a loss of time means a loss of money. The multiplicity of parts in some of the instruments on exhibition was astonishing. I was attracted by the complication of an instrument having a circle of about eight inches diameter, and although I could see little more than one side of the instrument I counted no less than 93 screws of all kinds, whilst others seemed evolved and contrived from the inner consciousness of some closet professor.

In one large combination instrument in the exhibition, there were, among other curious features, two small lamps for illuminating the horizontal circle under the three microscopes; one for the telescope, and one for reading the level and the two microscopes for the vertical circle, together with a multiplicity of mirrors to reflect the lights. No matter howsoever small the heat of the flames might be, here was the introduction of souces of error that would tend to complicate and mask the other defects of the instrument.

I had the opportunity of studying many of the recent and varied forms of portable transit instruments. Some there were that never should have been permitted to leave a workshop; others aiming at great stability by the use of very heavy cast-iron stands, yet introducing an element of error in having their adjustments for level and azimuth at the base. This seems very much like erecting a great solid building upon a movable foundation. It is granted that in the usual form of movable Y's for the adjustment of the transit axis level and of azimuth, two fertile sources of error exist, but many years since I readily and successfully overcame the difficulty by tightly clamping either movable Y after the last mechanical correction has been made to the adjustments. Troughton and Simms have in part since used a similar application. The frames of the later Coast Survey transit instruments are emphatically portable from their form and weight of metal; their telescopes have generally greater light-collecting power than the portable transits examined, whilst the character of the results is fully established by the rigorous method of discussing them. By the adoption of four foot-screws I have secured remarkable firmness; whilst the double frame gives not only great facilities for preliminary adjustments in the meridian, but enables the transit to be used for a latitude instrument by the Talcot method. Some of the portable transits in Europe hardly bear out that character, and would not be adopted in the mountains where our geodetic work is being carried; it was very evident that cast-iron was cheap, transportation easy, and time no object. And I found severer criticisms than mine passed upon particular instruments (designed for great surveys) by some whose opinions have much weight in the geodetic world; whilst one well known observer confessed, that were he to design a new instrument it would not have the form of that which he had planned, constructed and already used.

Although I made few efforts to examine the manufacture of lenses for telescopes and microscopes, those which I did see were generally of superior character. I was very much impressed with the thorough skill and knowledge of Shroeder, of Hamburg, who was making the lenses for the 15-inch equatorial of the new Potsdam observatory. An examination of some of his smaller instruments revealed marvelous precision of figure, whilst his means of testing the curvature of the lens was beyond anything I had seen or known. The computations for the curvatures of the lenses are very elaborate and exhaustive.

Without going into details of telegraphic longitude apparatus, electrical clocks and chronometers, etc., I may mention that I examined the base apparatus of Brunner, being constructed for the Spanish Geodetic Survey; and

had the greatest pleasure in examining the original base apparatus of Bessel in the Prussian geodetic office. The Brunner apparatus aims at the simplicity of the Borda thermometer, and is therefore composed of two four-meter bars of different metals, having largely different co-efficients of expansion. The lower bar is platinum; immediately above it is the brass bar of the same cross section. At one extremity of the compound, or rather composite bar, the two bars are joined, but are free towards the other extremity. At the free ends the upper bar has a slot in it that receives a piece soldered to the lower bar, whereby the upper surface of this piece is flush with the upper surface of the brass bar. Upon one is cut a series of graduated lines; upon the other a vernier. When the bars expand or contract through increase or decrease of temperature they do so unequally, and the difference of that change is read and is determined by the scale and vernier.

The base bars of Bessel are four in number, and each composite bar is formed of two bars of different metals of different rates of expansion for equal increments of heat. In this case the lower bar is iron and the upper is zinc. One end of each system is formed by the junction of the two bars, and thence the bars are free. Instead of a scale upon one and a vernier upon the other, the zinc bar terminates close to a small projection upon the upper surface of the iron bar, and the difference of expansion was measured by the insertion of long graduated wedges of glass in the space between the end of the zinc bar and the iron stud.

Either of these forms of apparatus has great merit in the extreme simplicity of the form and fewness of parts, and it appears to me that with thorough skill in the observer, accuracy of comparison with the given standard bar, simplicity and stability of the supports, and the proper means of effecting the contacts, the method is susceptible of great accuracy. But I was very far from being satisfied with the character of the supports and the methods and appliances of measurement. These, however, I discuss fully in my official report to the Superintendent of the Coast Survey.

Without detaining the attention of the Academy any longer, I may mention, in brief, the general conclusion to which I arrived. While I saw much of deep interest, there was no single instrument that I would unreservedly recommend for adoption in its entirety. What I principally learned was really *what not to copy.* And whilst awarding high credit to the instrument makers of Europe, and keenly alive to their courtesy, I am convinced that we do not need to go to Europe for geodetic instruments, although we should possess copies of their finest efforts for comparison with our own. With our own observers and mechanicians working in harmony and striving to attain the highest excellence, I firmly believe that we are fully competent to lead in this scientific effort. Both parties fully appreciate the fundamental requisites to success, and the character of the geodetic work of the United States demands that the mechanical means shall be adequate to the delicate manipulation and requirements of the most skillful observers.