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A Precision Two Crystal X-Ray Spectrometer of Wide Applicability with Worm Wheel Drive; an Improved Precise Method of Equalizing the Spacing of Worm Wheel Teeth

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This article describes the design and construction of a two crystal x-ray spectrometer for the study of radiation of wave-length from (but not including) the vacuum region to about 100 X.U. Versatility coupled with precision of angular measurement is obtained by the use of worm gears, the spacing of whose teeth has been corrected by a relatively cheap but effective lapping method herein described.

1. INTRODUCTORY

THE applications of the two crystal spectrometer are so varied that severe requirements are put on the designer of an instrument which is to be used for many purposes. In the absolute measurement of angles of reflection by Compton's method[1] it must be possible to rotate crystal B through large angles ($180°\pm 2\theta$) and measure these large angles with high precision. In this work and also for the investigation of the quality of crystals used it must be possible to work in negative orders as $(1, -1)$ or $(2, -2)$ and it is sometimes useful to work in mixed orders (n, m) or with two different kinds of crystal on the two tables so that a single rigid relationship between the motion of crystal pivots A and B must not be imposed.

For the study of rocking curves at zero dispersion, $(1, -1)$ or $(2, -2)$ order, it must be possible to advance the crystal angles in extremely small steps by fractional seconds of arc since rocking curves are often so narrow. Here high absolute angular precision is not the requirement but rather great angular sensitivity of setting coupled with reproducibility and stability.[2] Finally for work with hard radiation and certain other projected types of work it is essential to have quite accurate and convenient means of controlling the position and orientation (with respect to the crystal pivots) of the ion chamber and shielding lead slits through which the beam from the second crystal must pass, as well as the position of the x-ray tube and the shielding lead slits for the primary beam.[3] In our case the size, weight and complexity of the 30 kilowatt x-ray tube for which this instrument is designed calls for a stationary[4] primary beam

[1] A. H. Compton, Rev. Sci. Inst. **2**, 365 (1931). The instrument used by Compton for this work, constructed by the Société Génevoise, had two excellent divided circles one of which, however, since it controlled the motion of the ion chamber arm was hardly in a position to serve to the best advantage. In Compton's design the x-ray tube must be rotated about axis A which may be a disadvantage as S. K. Allison later pointed out. On the other hand an instrument by Gaertner Scientific Corporation built for Allison has the same scheme of motions as the one here described but is not adapted for absolute glancing angle measurements since with it "angular measurements of rotation through large angles about axis B cannot be made with great accuracy." See S. K. Allison, Phys. Rev. **41**, 1 (1932).

[2] DuMond and Hoyt, Phys. Rev. **36**, 1702–1720 (1930). This spectrometer has all the requisite motions although it is used with a moving x-ray tube and a fixed detecting system including an ion chamber mounted directly above a Hoffman electrometer. It has the great angular sensitivity, etc., required for the study of rocking curves *but absolute values of large angles cannot be measured with high precision.*

[3] T. R. Cuykendall and M. T. Jones, R. S. I. **6**, 356 (1935). These authors have a two crystal spectrometer design for the range $0.030<\lambda<0.215$A using a sine screw arrangement similar to that of F. K. Richtmyer and S. W. Barnes, R. S. I. **5**, 351 (1934). While excellent for shorter wave-lengths it cannot be used for negative or mixed orders as these authors point out nor will it serve for Compton's method of measuring absolute angles. The instrument of Richtmyer and Barnes permits all measurements and uses except the last mentioned.

[4] The tube could, it is true, have remained stationary without necessitating a stationary beam by mounting crystal A on a carriage translating on a slide midway between focal spot and crystal pivot B. This clever scheme is due to P. A. Ross while an equally ingenious unpublished

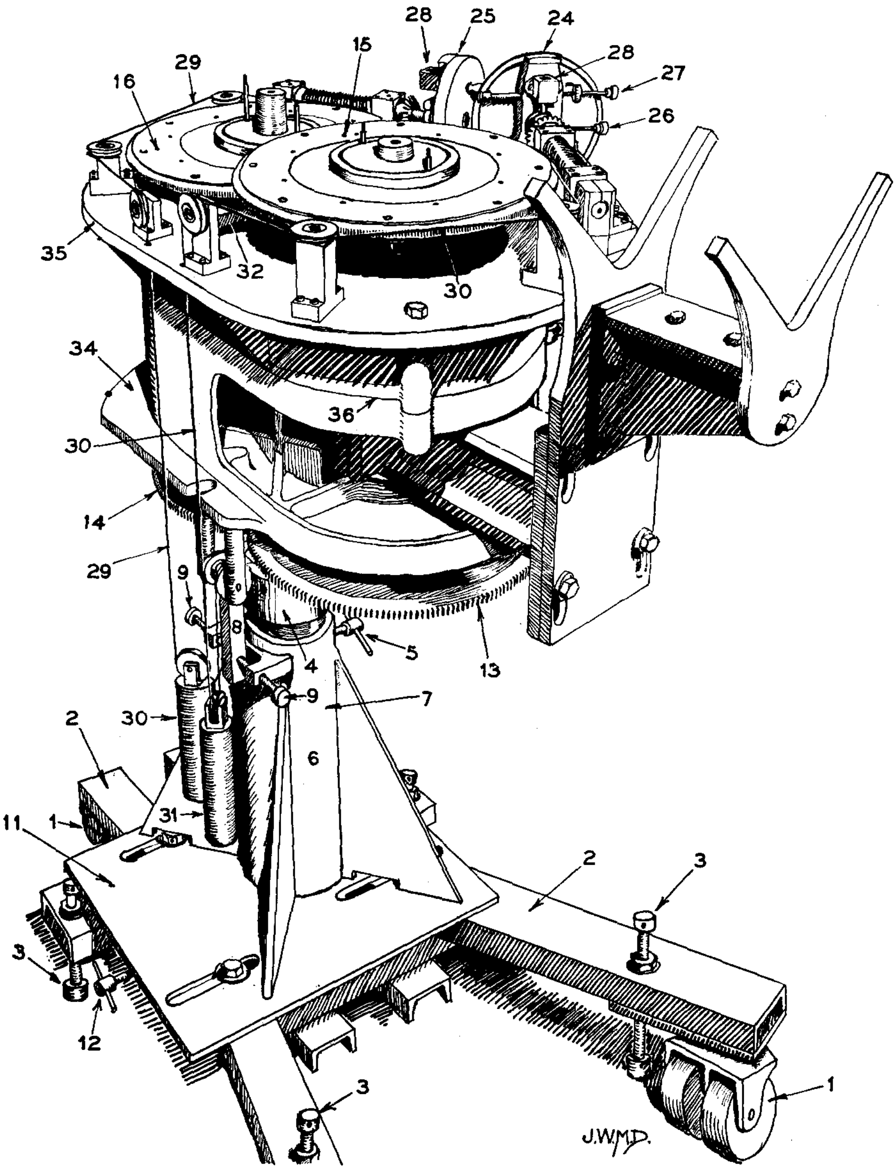

FIG. 1. Perspective view of two crystal x-ray spectrometer with crystal holders and dust proof cover removed from upper worm wheels.

which in its turn necessitates an instrument in which the line of centers of the two crystal pivots can rotate. Budget limitations which demanded so many simultaneous requirements in one instrument also prohibited purchasing high precision worm gears or high precision divided circles with their accompanying optical parts. We were thus led to the herein described method of originating a precise worm gear.

We make no claim for the *superiority* of any single feature of the instrument we are about to describe over similar features in the spectrometers referred to in our footnotes. The present design is noteworthy only in that it combines *in a single instrument* nearly all the virtues and functions which would only be possessed and performed by several of the other designs taken together.

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scheme of P. Kirkpatrick permits *both* stationary source and ion chamber window. The angle of emergence of the x-rays from the target surface however changes with the setting; in both of these schemes unless the tube is movable.

2. General Description of the Instrument

Referring to Fig. 1 (many parts also appear in Figs. 2 and 3 with the same numbering), the weight of the instrument can be lifted off the casters (1) provided in the base (2) by means of four leveling screws (3). The instrument is also adjustable as to height and orientation in a horizontal plane with a large nut (4) and clamp (5) for raising and clamping the main supporting column (6), (Fig. 3), in its socket (7) and a prong clamp (8) and tangent screws (9) for rough orientation. The foot plate 11 can be slid by the screw (12) to align the instrument with the x-ray beam.

Four rotational motions are provided, two of which (the crystal pivots) are highly precise while the other two, one of which turns the ion chamber around crystal B, the other the instrument as a whole round the same axis as that of crystal A, have high quality bronze worm gears which have not been corrected by lapping or calibrated for errors. These latter worm wheels (13), (14) under the machine have only half as many teeth as the upper precision worm wheels (15), (16) and hence they turn twice as fast for the same speed of rotation of their driving worms. Fig. 2 shows the mechanical coupling provided by means of one to one bevel gears, counter shafts (19), (20) and clutches (21), (22) so that when a spectrum is being explored the proper rates of angular rotation will be imposed on the various parts of the instrument. Shafts (19) and (20) only transmit rotation when clutches (21) and (22) are locked and then each of the lower worm wheels rotates at twice the angular velocity of the precise worm wheel just above it. If one takes the movable frame of the machine (not the base) as his system of reference the action of the counter shafts just mentioned insures, first, that as crystal B rotates with velocity ω on its table the ion chamber together with its shielding slits will rotate with velocity 2ω round the same center so as to follow the beam reflected from crystal B and, second, that as crystal A

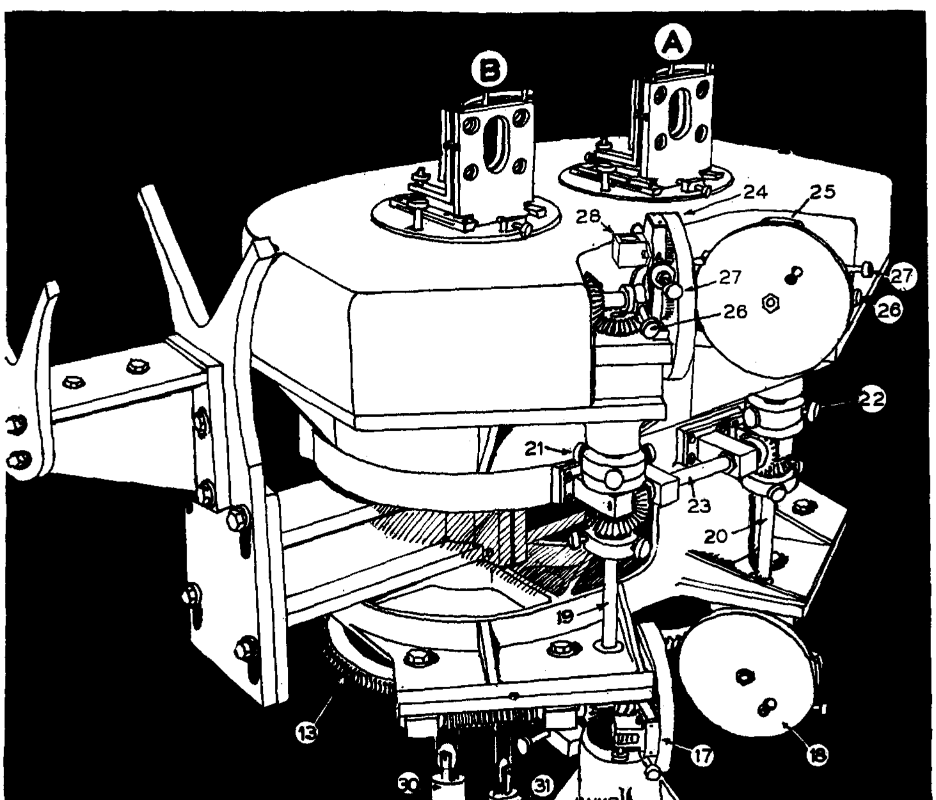

Fig. 2. Perspective view of front side of two crystal x-ray spectrometer showing mechanism of bevel gears, counter shafts and clutches coupling the upper and lower worm wheel drives.

rotates with the velocity $-\omega$ the base of the machine, the room and the x-ray tube along with the shielding slits for the primary beam will rotate with velocity -2ω round the pivot of crystal A. The intermediate beam from crystal A to crystal B is thus permitted to remain stationary along the line of centers of the crystal pivots. The shafts (19), (20) when their clutches are locked thus insure the rates of rotation required by the law of specular reflection which must invariably hold for all crystals and orders. For the exploration of a spectrum in the (n, n) order the horizontal counter shaft (23) can be used to lock the rotation of the vertical shafts (21) and (22) so that they, and consequently also the crystal pivots, have equal rates of opposite sign.

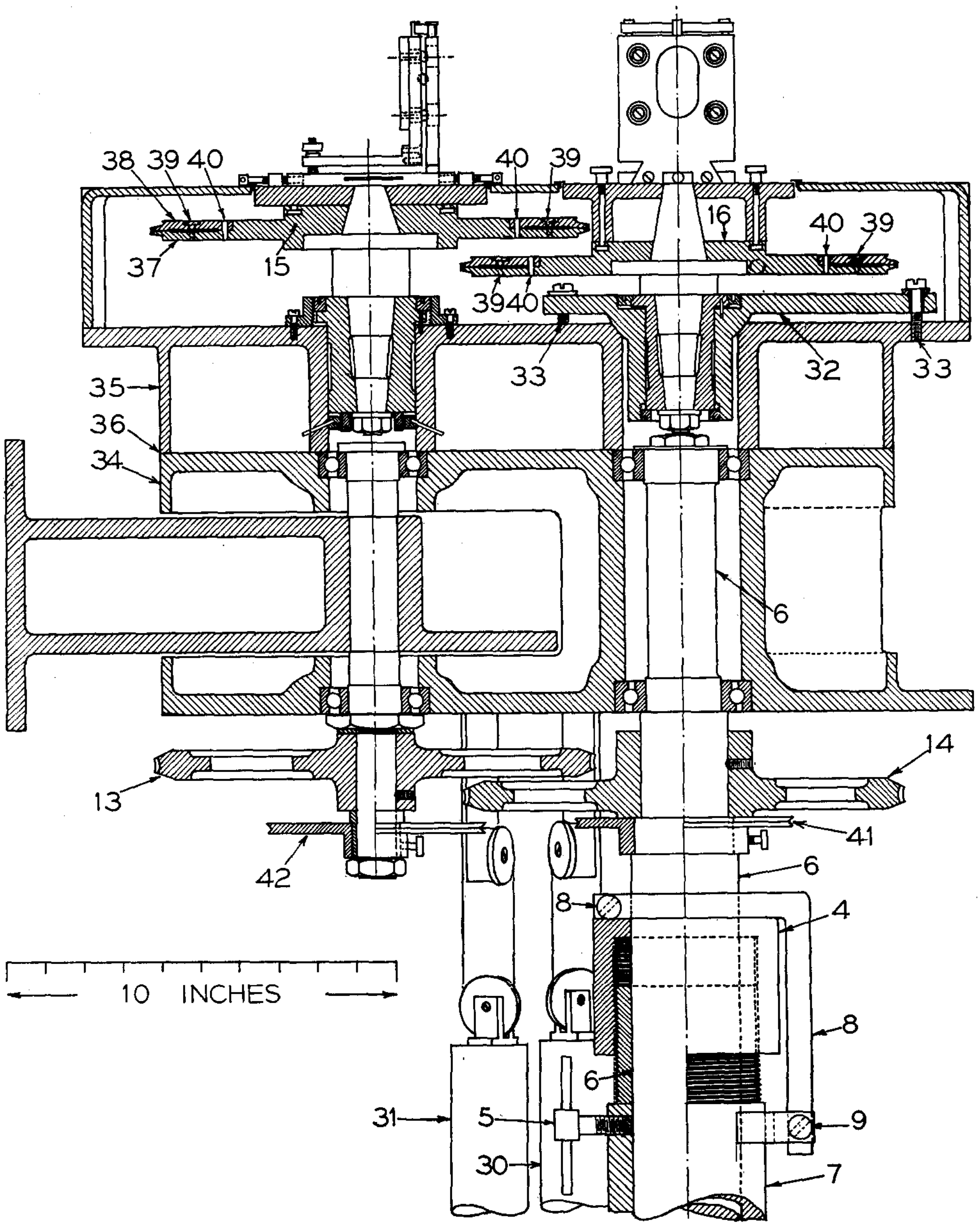

FIG. 3. Cross section through two crystal x-ray spectrometer along a plane through the axes of the two crystal pivots. (Slight deviations from this plane following the conventions of machine drawing avoid cross-sectioning shafts, ribs, etc.) Parts 5, 7, 8 and 9 have been rotated through 90° about the vertical supporting column the better to show them.

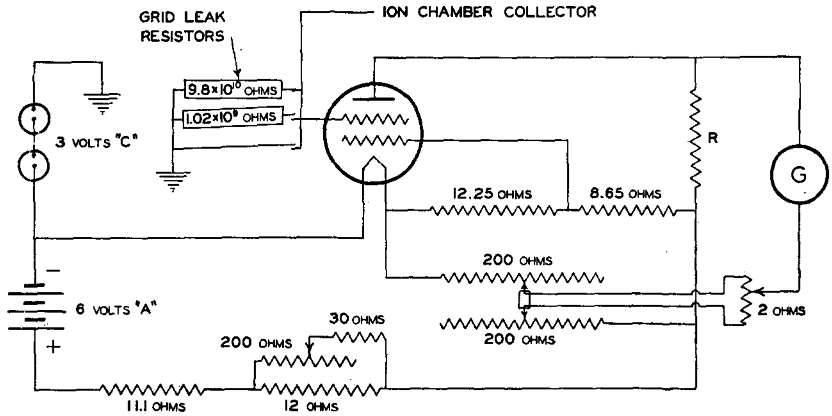

FIG. 4. Diagram of connections for ion chamber d.c. amplifying tube.

The rotation of the lower worm wheels can be read on the divided drums (17) and (18) attached to the lower worms to the nearest minute of arc. The precise angular rotation of the crystals can be read to one second of arc on the drums with their verniers (24) and (25), while for very slow rotation of the crystals by fractional seconds as in studying "rocking curves" a clamp (26) and tangent screw (27) with a small divided drum is provided for each precision worm shaft. A full rotation of each worm shaft corresponds to one degree rotation of the crystal and the number of rotations of each wheel may be read on the dial of a counter such as (28). The precise worm shafts are provided with hardened steel thrust bearings, the rotating member on the end of the shaft being a convex spherical cap contacting a plane stationary member accurately normal to the axis of rotation. Backlash is prevented in both upper and lower thrust bearings and also between worms and worm wheels by means of fish lines (29), (30), Fig. 1, each wrapping in grooves in the periphery of each upper worm wheel and round an adjustable drum coupled to each corresponding lower worm wheel (41, 42 Fig. 3). As this line unwinds off of the upper worm wheel, whose groove has twice the diameter of the lower drum, it winds up at the same linear rate on the lower drum which normally (as just explained above) rotates at twice the speed of the upper wheel. Thus the weights (30), (31) which maintain the tension in the fish lines necessary to remove backlash normally neither rise nor fall.

Fig. 3 is a cross section through the instrument in a plane passing through the two crystal pivot axes save that parts 5, 7, 8 and 9 have been rotated through 90° the better to show them. The construction permitting alignment of the axis of rotation of crystal table *A* to exact parallelism with the axis of table *B* is almost self-explanatory. The casting (32) which contains the bearing of table *A* is provided with a spherical zone fitting in a socket in the frame of the instrument so that the bearing axis can be adjusted for verticality with two degrees of orientational freedom by means of the screws (33) of which there are three symmetrically spaced about the axis at the corners of an equilateral triangle. Parallelism is obtained by means of a sensitive spirit level. Fig. 3 also shows the large ball bearings which support the frame of the machine and the ion chamber arm. As can be seen the frame of the machine consists of two distinct castings (34), (35), each heavily ribbed, which are joined at (36) and aligned by bolts and dowel pins. The two crystal tables and all of the precise mechanisms are on the upper casting which can be unbolted and lifted off the lower casting at any time since the vertical counter shafts (19), (20) are not continuous but have a break just below the clutches (21) and (22) across which rotation is transmitted by a simple scheme resembling an Oldham coupling.

The precise worms and worm wheels are covered with a dust tight cast aluminum cover whose upper face is machined truly plane and normal to the pivot axes. This greatly facilitates laying out the correct positions of lead slits, stops, etc. The crystal holders with their sliding carriages and tilting mechanism of conventional design are mounted on disk shaped tables which can rotate relative to their supporting worm wheels and be clamped thereto in any orientation by means of screws whose lower heads engage in Tee slots cut in the worm wheels. The design is such that the conical holes in the top ends of the steel crystal pivots on which those pivots were originally turned in the lathe remain exposed so that a trammel point can be engaged in them. This is a convenience for one of the steps of the method we use in aligning crystals,[5] as is also the large oval hole which perforates the crystal support.[6]

The cylindrical ionization chamber is supported in the V cradle attached to the swinging arm clearly visible in the figures but this cradle can be unbolted and anything else attached to the arm if desired. The present chamber has been described in a previous article[2] save for the fact that instead of a Hoffman electrometer for measuring the ionization currents a Western Electric d.c. amplifier tube (WE-D96475) mounted directly on top of the chamber in an evacuated metal shielding case is used. A switching device inside the vacuum but operated from without through a ground joint permits the selection of any one of three grid leaks to suit the currents to be measured. The very simple diagram of connections, Fig. 4, for the d.c. amplifying tube shows one feature worth mentioning. The extra biasing battery C consisting of two ordinary dry batteries eliminates the galvanometer drift which which would be caused by the decline in grid bias with declining voltage of the main storage battery supply if this were also required to perform the function of furnishing the grid biasing potential along with the rest of its work. Resistances both fixed and variable are carried immersed in oil in a small well shielded box mounted on the ion chamber near the tube.

Two covers of aluminum not shown in the cuts, one for the crystals and lead stops on top of the instrument, the other to cover the gears and worm drums on the side, can be attached and locked in place with a single Yale lock to insure that the history of the instrument shall be known to the user.

3. Method of Removing the Errors of Tooth Spacing in the Precision Worm Wheels

The wheel design we employed for correcting the errors of tooth spacing in the worm gears has been known for many years.[7] The cast iron worm wheel, as can be seen in the section Fig. 3, is split into the wheel proper (37) and the ring (38) whose conical and plane surfaces are scraped to an excellent fit against the corresponding surfaces of the wheel. The teeth are cut half in the wheel and half in the ring. The ring is held fixed to the wheel with eight rather loosely fitting screws (39) and eight taper dowel pins (40). The general idea is to lap the worm or preferably a dummy worm into the split wheel with emery, the wheel being allowed to turn freely on its working bearing and the ring being shifted in position from time to time with respect to the wheel between stages of lapping.

Our specific contribution to the split wheel method of equalizing the errors which the authors believe to be new and original with them is the *schedule of shifting the ring with reference to the wheel between successive stages in the lapping process through successive integer powers of one-half a revolution.* Contrary to the most widely entertained belief a careful analysis of the situation will convince the reader that the equality of spacing of the dowel pins (which is also most easily obtained both radially and circumferentially by successive reamings and likewise with intermediate shiftings through integer powers of half a revolution) is *not* the essential feature insuring perfect tooth correc-

[5] In the paper by DuMond and Hoyt already referred to in reference 2 our method of aligning crystals so that the intermediate beam from crystal A to crystal B shall be parallel to the line of centers of the crystal pivots is fully explained, pp. 1715, 1716. The optical reflection method serves to give correct settings generally closer than one minute of arc so that little time is lost in "finding a line" the first time with the x-rays. Bearden has recently announced that a comparison of optical and x-ray reflections from cleavage planes fails to agree precisely as to the orientation of the reflecting surfaces.

[6] This hole facilitates observing optical reflections with a Gauss eyepiece from both sides of a parallel optical flat temporarily mounted in place of the crystal.

[7] We are indebted to F. K. Richtmyer for pointing out to us after this work was completed the following references to the use of the split wheel and dowel pin design: *Handbuch der Astronomischen Instrumentenkunde* **1**, 145 (1899), the American Machinist **20**, 531 (1897); **21**, 303 (1898).

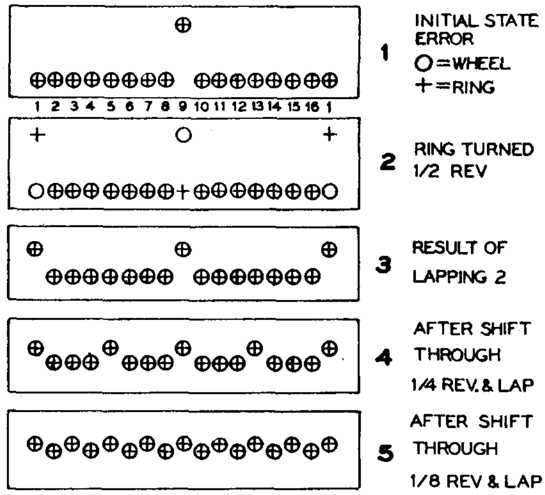

FIG. 5. Error graphs of an ideal (16 tooth) split wheel all of whose teeth have initially the correct positions save one (number 9) showing how the principle of shifting through successive integer powers of half a revolution operates in an optimum way to reduce and uniformly distribute the initial error.

tion.[8] The only function of the dowel pins is to facilitate a match between the partially equalized teeth on the wheel and on the ring so favorable as to require only a very small amount of lapping to restore flush tooth surfaces. Since, however, it is very desirable to lap off as little metal as possible the use of a number of dowel pins equal to the highest power of two by which the number of teeth on the wheel is exactly divisible is strongly to be urged. Since there were 360 teeth this called in the present case for eight dowel pins. The schedule of shifting the ring relative to the wheel through successive integer powers of half a revolution can, however, be carried several stages beyond the limit thus set by the number of dowel pins (as we shall immediately show) if the wheel is provided with a Tee slot so that screws through the ring whose heads engage in the Tee slot can be made to clamp wheel and ring together in *any arbitrary* orientation.

Referring to Fig. 5, the action of the lapping schedule in integer powers of half a revolution is best understood by considering the error graph (in which the errors of tooth position to large scale are plotted as ordinates against the ordinal number of the tooth as abscissa) for an ideal wheel all of whose teeth are spaced perfectly save one (the middle one in stage 1). After the ring is shifted through half a revolution on the wheel the erroneous tooth on the ring will be adjacent to a correct tooth on the wheel and the erroneous tooth on the wheel will be adjacent to a correct tooth on the ring. This situation appears in graph 2. As the worm laps over these regions the error in the erroneous tooth, say on the ring, will tend to be one-half removed and one-half copied in the correct tooth on the wheel so that after this first stage of lapping both wheel and ring will now have the error graph shown at 3 with two equally spaced errors half as large as the single initial error. If now the ring is shifted on the wheel through a quarter revolution, $(\frac{1}{2})^2$, and lapped, an entirely similar action will give four errors equally spaced about the wheel each of which is only one-quarter as great as the original error; see graph 4. Finally a shift through one-eighth revolution $(\frac{1}{2})^3$ with subsequent lapping gives the graph at 5. Roughly speaking the fate of each initial error in an actual wheel will be just the same as we have outlined for the single isolated error on this ideal otherwise perfect wheel, each error being halved and distributed in the way described just as though all the other errors were not present. In actual practice, however, since the worm is in contact with several teeth at once there is also a tendency (not as marked as one at first expects) for the error in any tooth to be partially copied in the teeth on either side. On the error graph this tends to make the curve as a whole assume a little smoother shape so that there are no sudden jumps between adjacent teeth. For this reason it is not necessary to shift the ring on the wheel through successive angular intervals *exactly* equal to successive values of $(\frac{1}{2})^n$ if the number of teeth make this impossible. Thus the schedule for a wheel such as ours with 360 teeth would call for successive shifts through 180°, 90°, 45°, 22°, 11°, 6°, etc., if it were carried beyond the first three steps permitted by the dowel pins. It is evident that such a schedule can always be devised in such a way that the position of the ring on the wheel never differs from that prescribed by the ideal observance of the formula $(\frac{1}{2})^n$ by more than half a tooth

[8] The writer of the article in the American Machinist, **21**, 303 (1898), states in no uncertain terms that the strict equality of spacing of the four dowel pins in his wheel was essential to the process of tooth error correction!

space.[9] Of course when the dowel pins are no longer available to insure the best match more care is necessary in shifting the ring on the wheel to insure a match that will require only a minimum amount of lapping.

It may at first appear strange that the magic base is $\frac{1}{2}$. The incredulous reader can soon convince himself that this is true by following through a theoretical schedule like the one shown in Fig. 5 but with some or all of the shiftings through powers of say $\frac{1}{3}$ revolution or any other value not included in the formula $(\frac{1}{2})^n$. The errors will not then vanish uniformly and rapidly around the wheel and it will be easy to see that $(\frac{1}{2})^n$ is the rationally prescribed shift simply because the wheel is split into *two parts* instead of three or more.[10]

Space limitations forbid the inclusion in this article of many detailed points which our experience in constructing these wheels has taught us such, for example, as the effects of noncoincidence by minute amounts of the axis defining rotation of the ring on the wheel with the axis of rotation of the wheel in its bearing,[11] design of the hob and the extra allowance on the teeth for lapping, minimization of wear on the dummy worm during lapping by continual shifting of the pitch point, dangers of excessive lapping, methods of gauging depth of lapping, precautions in reaming the dowel holes, etc., etc. These we hope to publish in the near future in an engineering journal.

[9] The idea of extending our lapping schedule by this approximate observance of the formula $(\frac{1}{2})^n$ only occurred to us after the worm wheels here described were completed and tested. It could not be applied to them as they had no Tee slots. We have every reason to believe it sound and it will be applied on the worm wheels for driving the 200-inch telescope. The principle should be of great utility since it permits the designer to give his wheel *any number of teeth he wishes* (though by so doing he may of course be obliged to sacrifice the convenience of the use of the dowel pins).

[10] One is at first tempted to analyze the actions of lapping schedules on the error graph by expressing this graph as a Fourier series. We believe, however, that the method here presented is simpler and easier.

[11] This makes advisable provision for centering the wheel on its pivot by very minute shifting after it has been lapped —a precaution unfortunately not observed in the present design. The splitwheel method of course only equalizes the tooth spacing correctly with respect to the axis defined by the rotation of the *ring on the wheel*.

4. Optical Tests of the Precision of the Worm Wheels, Worms and Thrust Bearings

For the optical test aluminized optical flats 6″ in diameter were mounted on the worm wheels on subsidiary bearings so that they could be sensitively set in any position relative to the worm wheel by means of a clamp and tangent screw. The angular rotation of different worm wheel intervals could be compared for slight plus or minus deviations from an arbitrary fixed interval very near to the correct standard value and defined by two line filament lamps fifty feet away from the mirrors by observing the reflections of these line filament lamps with an excellent 4″ refracting telescope fitted with a one hundred power microscope in its eyepiece. One of these line filament lamps was mounted on a micrometer screw and slide to facilitate setting it. The intervals on the worm wheels were so uniform that their deviations from equality with the fixed interval defined by the lamps could all be easily read in the microscope field with a filar micrometer in the eyepiece. The central image of the diffraction pattern is about one second of arc wide with a four-inch objective and without too much eye strain it can be split in half to a small fraction of its width. The minute differences between nominally equal intervals on the worm wheel were measured all around the wheel for three different sized sets of intervals, namely, 90°, 15° and 3°. The algebraic sum of these four observed differential errors in the 90° intervals would be zero if the standard comparison interval defined by the line filament lamps had been exactly 90°. The observed differential errors are therefore simply expanded or contracted uniformly so as to effect "closure" in the same manner as a surveyor distributes the error of closure in a traverse. The algebraic sum of the six observed differential errors in the set of six 15° intervals corresponding to each 90° interval was compared with the measured error of that 90° interval and these six 15° errors were expanded or contracted to effect closure as before. In a similar way the errors of closure of each set of five three degree intervals were next adjusted to fit the corresponding corrected fifteen degree interval. The cumulative error of

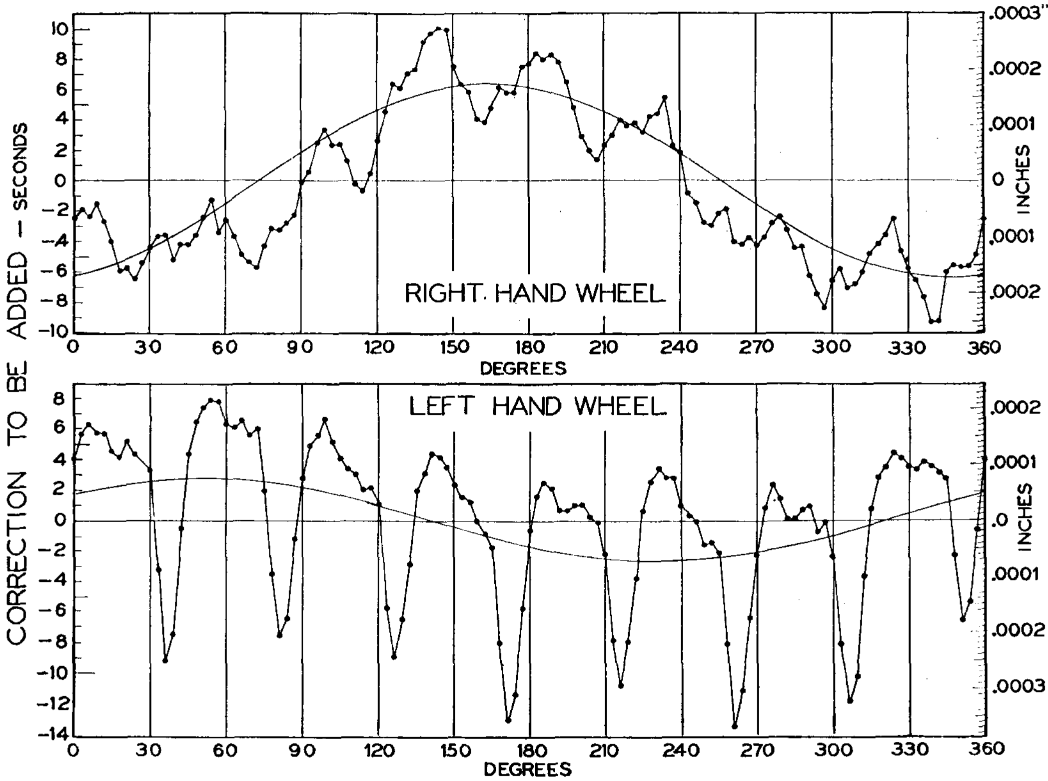

FIG. 6. Error graphs obtained by optical calibration of the two worm wheels in the present x-ray spectrometer. The deviation of every third tooth from its correct position is shown both in seconds of arc and in inches. The sinuosoids determined by a Fourier analysis show the eccentric error caused by the fact that the pivot axis on which the wheel turns as a whole fails to coincide with the axis of rotation of the ring on the wheel by a little over one ten-thousandth of an inch in the worst case. The incorporation of sensitive centering screws would have made the elimination of this error simple.

every tooth was then obtained by summing algebraically the three degree errors so adjusted. By this method of adjustment never more than five observed differential errors are in effect added to obtain the cumulative error of any tooth. It is necessary of course to translate the filar micrometer readings of deviation into absolute angular terms but the multiplying factor for doing this can be obtained by a measurement on the worm wheel drums themselves with ample precision.

By setting the line filament lamps about $1\frac{3}{4}''$ apart at 50 feet distance a standard rotation interval for the mirror of five minutes of arc could be defined and with this the uniformity of rotation of the worm wheel could be tested for twelve adjacent five minute intervals corresponding all together to one revolution only of the worm. This tests the helical uniformity of the worm on the axis defined by its journal bearings and also the freedom from any axial motion which might be introduced in the thrust bearing. For these small intervals no deviations from strict equality could be detected within the sensitivity of the method which was certainly better than $\frac{1}{3}$ of a second of arc rotation of the worm wheel. Differences of a fraction of a second could be detected according to whether a given setting were made with or against the backlash tension but such settings if always made by approaching the division from the same direction were remarkably reproducible.

Fig. 6 shows the error graphs actually obtained for the two worm wheels and we call attention to the smallness of the residual error on the better of the two after making abstraction of the eccentricity (smooth sinusoid). The scale of errors in Fig. 6 is expressed in inches measured on the pitch circle as well as in seconds of arc and it is seen that no deviation from the mean tooth position seriously exceeds a ten-thousandth of an inch on the right-hand wheel after making abstraction of the eccentricity.

The error graph for the left-hand wheel with its eight almost identical sharp narrow valleys is a most interesting confirmation of our analysis of the action of our lapping schedule in integer powers of half a revolution. The machinist who hobbed the teeth on these worm wheels reported that the left-hand one had a hard spot near the periphery at one point only such that he was in great fear of breaking the hob every time this point was passed. The other wheel was quite uniform and homogeneous. The result leaves little doubt that a single concentrated initial error of say $2\frac{1}{2}$-thousandths of an inch caused by this hard spot and localized over only a few teeth was distributed into eight equally spaced and very nearly identical errors of one-eighth the original value each (0.0003″). Their equality of shape and amplitude is strong evidence for this. The narrow concentrated nature of each valley shows how slight is the aforementioned tendency of the worm alone to smooth out the error curve. It is easy to see what an immense improvement one or two more stages of our lapping schedule would have made in this "underprivileged" wheel.

5. Cost of Construction

The labor on the entire construction of the instrument including the worm wheels was approximately 2300 man hours. Cost of the castings and materials totaled only about $150.00.

6. Acknowledgments

We are indebted to Dr. G. H. Worrall of the Mitchell Camera Corporation of Hollywood for his kind cooperation in hobbing these worm wheels on a precision Barber Coleman hobbing machine. We thank Dr. John Anderson and Dr. W. V. Houston for lending us the necessary optical parts for testing the worm wheels.

The staff entrusted with the construction of the 200-inch telescope has on the strength of our present results decided to adopt the method here described to originate precision in the large telescope driving worm wheels and we thank them for their very stimulating and helpful interest.

The funds for the construction of this spectrometer were derived from the gift of Leon L. Watters of New York City known as the Watters' Memorial Research Fund, given as a memorial to Dr. Watters' wife, Frances Hayes Watters. We are grateful for this opportunity to express our appreciation of his gift.

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An Interrupted Arc for Spectral Analyses*

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Introduction

In the analysis of materials by the spectrographic method one is always confronted with the problem of inserting the material into the arc in such a way that the sample will be readily and evenly consumed. The oldest and no doubt the simplest method is that of placing the sample into a small cavity which has been drilled into the end of a vertical cylindrical electrode. Mannkopff and Peters,[1] for example, have developed this method to the extent of determining the cavity depth best suited for various substances when they have different melting points. When the sample is in the liquid

* Aided by grants from the American Medical Association, the C. M. Warren Fund of the American Academy of Arts, the Rockefeller Foundation and the National Research Council.

[1] R. Mannkopff and C. Peters, Zeits. f. Physik **70**, 444 (1931).