Science Project Summary

Cost: $0-100 About These Ratings	Difficulty: ■■■□□	**Danger 1: (No Hazards)**	Utility: 😎

About Various Things, Mainly an Instrument for the Very Precise Measurement of Length

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by Albert G. Ingalls
August, 1954

■ OF ALL MEASUREMENTS length is the most fundamental. Almost all physical quantities are measured by the motion of a pointer on a dial or by the distance between two objects or images Thus length becomes the analogue of mass and time, the remaining quantities of the basic dimensional trinity. Most scientific instruments are designed to convert an unknown quantity into a convenient length, usually a few inches. A device capable of yielding a precise measure of length on the order of six inches can become one of the most useful and powerful instruments in the amateur's tool kit. With it he not only can check the accuracy of other instruments but can construct the variety of scales indispensable for gathering precise data in all branches of science.

Several months ago Roger Hayward, the versatile illustrator of this department, mentioned that he had recently built a traveling microscope and wondered if it might not hold some interest for the amateur fraternity. "This device," he wrote, "affords one of the nicest ways of measuring lengths of a few inches that I know about. The traveling microscope is just what the name implies: a microscope mounted on a carriage moved by a screw through a measured distance.

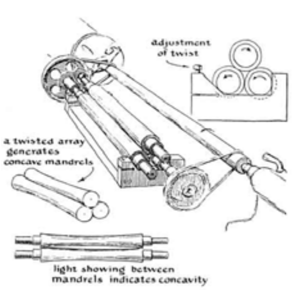
"The design of the carriage and its driving mechanism is much the same as the design of a ruling engine-but without the requirement of millionth-inch precision. At the outset let it be said that this is my first traveling microscope and I have no illusions about its perfection. Use has demonstrated that the frame could have been a bit heavier; the thrust bearing is suspect, and the ways could have been sturdier. Nevertheless, building it was fun, and no gadget in my shop has proved more useful.

"The project was really undertaken to try out a method of grinding the ways. After I had proved the method, it seemed rather a waste o$ time and energy not to complete the instrument. I haven't the foggiest idea of what the pitch of the screw is, and I have never been curious enough to lay hands on a standard to find out. In spite of these shortcomings the machine is capable of a precision of one part in 60,000 over a range of six inches, and with this accuracy it is possible to make fair measurements of coefficients of expansion, shrinkage of concrete and other physical properties.

"I have also made a carriage attachment which can rule scales; in fact, I used it to rule the scale of the instrument itself. A number of linear scales have been ruled with one thousandth of an inch spacing, and once I ruled a bit of grating. The rulings were half an inch long and spaced five 10,000ths of an inch apart. An indication of the instrument's precision is given by the fact that the two yellow lines of mercury are clearly resolved by this miniature grating-but the sodium lines are not.

"The traveling microscope consists of six major components: the carriage ways, the screw, bearings for the screw, the nut, the carriage and the microscope.

"The steel ways and spacer for the end plate are made from three pieces of 3/4-inch stock about 10 inches long. It is important that the carriage move in a straight line without rotation, because often you want to measure objects a foot or more away. On one occasion, for example, I measured the coefficient of expansion of Lucite while the sample was in an electric furnace. The measurements were taken through small windows. In such situations the mandrels (bars) that serve as ways obviously must be straight, although they need not be round.



A primitive method of generating straight mandrels

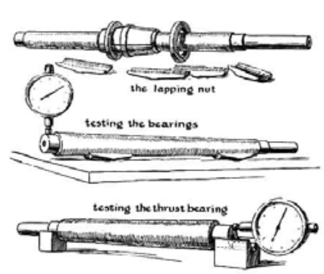
"It occurred to me that the necessary straightness could be generated by the primitive method of wet-grinding three mandrels together in a manner analogous to the making of three flats. This time-honored method depends on the fact that if any three surfaces make perfect contact when tried in all possible combinations, all must be plane. In the case of mandrels, the method has the attractive feature that the three can be ground together in one continuous operation. The method will not assure roundness, but this is not a requirement of the ways. The sketch to the left shows the setup.

"It is apparent that two cylinders can lie in contact with each other along their whole length if one is barrel-shaped and the other spool-shaped. A third cylinder could not lie in contact with this pair, however. In the grinding setup it would abrade the center of the barrel-shaped member and the ends of the other. If an array of three stacked cylinders is twisted slightly, a fit is possible if all taper from the ends to thinner waists in the middle. This condition can be tested by holding two cylinders in contact up to the light. If a position can be found where light can be observed between them, then the mandrels are concave and the array was twisted during grinding. A slight adjustment of the end bearings of the grinding fixture will correct the matter.

"A few evenings of grinding produced quite acceptable cylinders. The design of the bedplate and bearings of the grinding fixture is apparent in the illustration. By making the pulleys of the two lower mandrels of different sizes, I was able to get each of the three mandrels to grind on the others when they turned. The upper mandrel runs free, and grinding pressure is supplied by its weight. The assembly is belted to a rod chucked between centers in the lathe as shown. The mandrels are identical. Symmetry can therefore be maintained by exchanging and reversing the individual pieces frequently during the grinding operation.

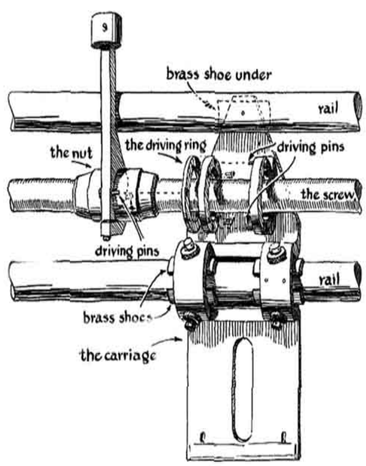
"Separate stock is used for the screw. The ground mandrels become contaminated with carborundum, which would dull the thread-cutting tool. The screw stock is chucked between centers and carefully trued. I cut 40 threads per inch and, to assure a screw of top quality, took many fine shavings. It is desirable ~ that each cut proceed from end to end e without any interruption to sharpen tools, so that you do not have to pick up a cut in the middle of the screw. The cuts vary in depth from five thousandths to five 10,000ths of an inch. The two sides of the thread are cut with the mandrel turned end for end. This distributes errors of run which might otherwise be transmitted to the work by the lead screw of the lathe.

"A steel nut about three inches long [*top of illustration at right*] was split into four segments and used to lap the thread. As the lapping proceeded, the segments of the nut were frequently turned end for end. Measurements of the diameter of the screw (with wires and a micrometer caliper) and the disappearance of dark rings during the process of lapping were taken to indicate that a fair precision was being



Testing the screw and the nut for a traveling microscope achieved. The outside of the nut was tapered so that steel rings could be slipped on to hold the nut segments together. Being rigid, they tended to produce a screw of uniform diameter.

"By resting the screw in parts of the lapping nut and measuring the bearing surfaces with a dial indicator [*center drawing*] I found that the axis of the finished screw no longer coincided with the axis of the bearings. This was corrected by local lapping with emery cloth on the offending surfaces. The end of the screw, which was to act as the thrust bearing, was found to be at an angle to the axis of the screw and was similarly corrected [*bottom drawing*]. Investigation later disclosed that this error originated from an error in the headstock of the lathe and demonstrated the fact that, although the flexibility of a lathe bed is small, it is sufficient when operating at this level of precision to generate and transmit errors even when the work is mounted between centers.



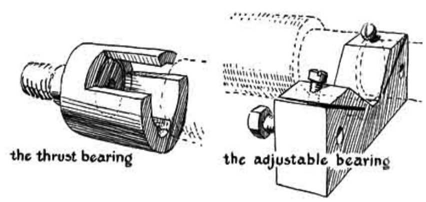
The carriage assembly of a traveling microscope

"The 'working' nut for the finished instrument was cut with a boring bar. The nut is about 2-1/2 inches long. An arm attached to it rides on one of the cylindrical ways and prevents the nut from rotating [*drawing to left*]. Two pins fitted into the nut, one above and the other below the screw, push the carriage through a set of rings, one of which is attached to the lower side of the carriage. The carriage ring, like the arm, is fitted with a pair of pins, but these are placed on either side of the screw at 90 degrees from those on the arm. Motion is transmitted from the tips of one set of these studs to those of the other through a floating gimbal ring. The object of this arrangement is to permit the nut to wobble without affecting the smooth travel of the carriage. Drunkenness in a screw is a common defect, and the gimbal ring renders it harmless-if the ends of the studs always lie in a plane. This requirement is met by making the gimbal ring in two parts, like a pair of washers screwed together, so that the studs pass through one part and press against the other. It is as though the studs pressed against the bottom of holes drilled from opposite sides to a plane lying precisely at the midpoint of a solid ring.

"The carriage is supported by five brass shoes, four of which bear on the *top* of the front rail and the fifth on the *under* side of the back rail. This permits the carriage to extend out in front of the instrument.

"The mandrels are assembled to a pair of end plates clamped together and drilled as a unit, so that the holes will be spaced evenly and will assure parallelism of the ways. The shoulders at the ends of the mandrels make a snug fit with the end plates. After assembly, the ways are tested for twist by laying a optical flat face up on the carriage an directing a telescope at the image of an object reflected in the mirror. The image should not move up or down as the carriage crosses the ways. A twist in the ways, incidentally, introduces error only if the cross-hair in the telescope is not vertical. All three mandrels are used, two for the ways and the third, beneath the screw, as a spacer for the end plates. The back of the instrument is made of a steel plate, 1/8 inch by 2 inches, fastened to the end plates. It carries a simple leg in its center.

"The two front legs are micrometer screws. Details of the thrust bearing for the screw and the adjustable head bearing are shown on the right. The sides of the thrust bearing are cut away so that it can be made a little too small to fit the end of the screw. It is merely the closed end of a leaf bearing relieved in the center and at the edge to avoid irregularities in the end of the screw. The lower bearing surfaces are on stiff members, whereas the upper one is thin enough to be limber and act as a spring to hold the screw against the lower surfaces. By too small I mean one 500th of an inch or less. The end of the screw is polished so that wobble may be studied by reflection and corrected by local polishing.



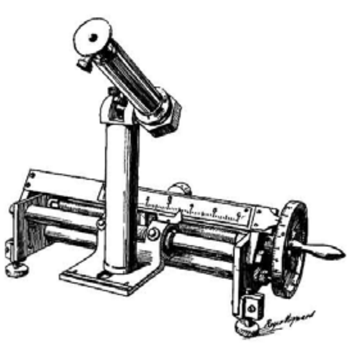
The thrust bearing of a traveling microscope

"The carriage may be fitted with almost any microscope or telescope, provided the eyepiece is equipped with cross-hairs. Experience has shown that one of the most convenient is a small telescope of 3/4-inch aperture which can be focused from six inches to infinity. A second lens an achromat of l-1/2 inch focal length fitted to the end, serves for objects an inch or so away.

"A handwheel with 125 divisions indicates motion of the carriage in .0002inch units. A scale divided into .025-inch units identifies the particular turn of the screw. The instrument is completed by equipping the base with leveling screws.

"What about corrections for variations in temperature? Most measurements can be made in one setting and in a situation which avoids wide temperature swings. My home is thermostated so that it stays about 70 degrees Fahrenheit plus or minus five degrees. The temperature coefficient of steel is available from handbooks, of course, and this value plus that of the material under measurement can be taken into account. In other cases one is primarily interested in relative and not absolute measures. Temperature factors then vanish from consideration. This is true, for example, in the case of spectrum plates, where it is desired to ascertain the relative position of the lines and not their absolute distance.

"The problem of temperature really stumped me on one occasion, however, when I set out to measure the coefficient of shrinkage of two types of concrete which I planned to use in the construction of a building. I cast specimen cylinders of each type of concrete and set them on blocks behind the instrument. On each specimen, painted white, I marked two sets of ink dots about 5.75 inches apart. Each set consisted of five dots about .025 of an inch in diameter and separated by a similar distance. In projects of this kind it is interesting to make measures in sets. Averages of such sets give reproducible results within a few 100,000ths of an inch even when the individual measures vary by several 10,000ths. Readings were made at each edge of each dot-20 measures in each complete set. The average of the readings from one end subtracted from the average of those from the other end gave the dimension under study. Measures were repeated every few days, and the slow process of shrinkage over a period of 50 days was clearly recorded.



Over-all view of the traveling microscope

"Between measurements the cylinders were stored outside where they would be subjected to weather variations. They were brought indoors about an hour before measuring so they would reach the same temperature as the instrument. Since the humidity affects the rate of evaporation from concrete, and hence the rate of heat flow, it is anybody's guess what the temperature of the sample really was on any occasion. Two authorities provided information about the temperature coefficient of concrete: one said it was slightly higher than that of steel (about one part in a million per degree centigrade higher) and the other said it was the same amount lower than that of steel. While my measurements fluctuated fairly widely, I learned what I wanted to know: the difference between the two kinds of concrete was too small to be of consequence. I had been led to believe that one type shrank significantly more than the other.

"Another useful application of the instrument is making scales. When I built the traveling microscope, I needed a six-inch scale divided into .025-inch units. The completed instrument is shown in the illustration on the next page. Its scale is etched on brass. The ruling is made with a gadget which fastens onto the carriage. It drives a scriber which rules through the slot in the carriage. A crank moves the scriber back and forth, and a cam lifts it on the return stroke. The material used for the scriber varies with the substance being ruled. For glass I use a diamond chip or shaped Carborundum (a single crystal). For Lucite and other soft materials, hardened steel retains a satisfactory cutting edge. The scriber-holder slides over an adjustable cam which permits ruling long or short lines as required. The ruling device is mounted on the bench with the work on the carriage so that the turning of the crank will not jiggle the instrument. The work is advanced by turning the wheel by hand. As mentioned previously, this instrument is not designed for the production of gratings. Nevertheless it is sufficiently precise to meet most requirements of an amateur's shop."

EACH AUGUST for the last 15 years the Cleveland Astronomical Society has entertained the city of Cleveland with a public telescope and star party. These parties have made Cleveland more astronomy-conscious than any other American city. James L. Russell, their organizer, says:

"We have had as many as 10,000 people in the public park where we hold them. The city turns out the park lights; we line up 35 of our homemade telescopes, and while a long line moves slowly past each telescope a professional astronomer addresses the crowd from a sound truck. After looking at the moon or a planet the people sit on the grass and watch the astronomical movies that we show, or study the celestial objects that we point out in the sky with a huge searchlight. We have so many people that it takes three evenings to run them all through. You would have to attend one of these parties to realize their magnitude."

During the rest of the year Russell leads Tuesday evening classes in telescope-making at the Cleveland Museum of Natural History, which has equipped a large laboratory for the amateurs. He says: "We have 40 people working at a time, and in the last five years they have made t350 mirrors. There is always a waiting list of about 175 applicants. It is wholesale production-the largest class in telescope making anywhere. We have 16 mirror-grinding pedestals, places for 40 people to polish mirrors at one time, a darkened place for the Foucault test, hand tools galore and machinery for making mountings-a lathe, drill press, band saws, a jig saw, sanders. Some grind or polish while others hammer and saw. It is sociable as well as astronomical. The din and dust are terrific, with 50 people in the huge room grinding, polishing, hammering, hollering and yapping their heads off, all at the same time, from five until nine. For each one who finishes the grinding stage we have 10 waiting to begin. It takes two years to work one's way to the head of the waiting line.

"Those who have made two or more mirrors, including myself, act as instructors five at a time. No one is paid; for us it is recreation and we just love it. Some bring lunches, the gal members cook them, and we grind with one hand and eat with the other. There is a rule that those who finish their mirrors must treat the entire gang to ice cream and cake, and this alone practically feeds us at most of the sessions."

The gregarious mass production of telescopes in Cleveland does not aim at perfection but primarily at making a large number of people happy with telescopes good enough for most uses. Russell is an organizer and leader. He says: "I am a lawyer, not a mechanic, and definitely not one of those who can turn out a perfect mirror, though as a beginner many years ago, using *Amateur Telescope Making*, I made 6-inch, 8-inch and 10-inch Newtonian telescopes and a Cassegrainian. Nor are many of our group scientists. While we have had chemists, physicists, physicians, engineers and many science teachers from the schools, many more are truck or taxi drivers, barbers and streetcar conductors. A large majority know neither paraboloids, hyperboloids nor other conic sections, and a few don't know the business end of a screwdriver."

Telescope making is no longer as exclusive as it used to be. During the classic 19th-century mirror-making era in England, D. P. Barcroft has found, there were actually no more than a few dozen amateurs who made telescope mirrors. There were even fewer in the U. S. until 1926, when SCIENTTFIC AMERICAN provided a handbook on telescope making and began to publish articles on the subject in practically every issue (the number of issues has now reached 314). For years the hobby remained "snobby"- not a sport for everybody-because astronomy seemed too intellectual and mirror-making too perfectionist. Telescope making has kept its attraction for those who enjoy it as a high-precision sport in itself, but it has also come to appeal to more and more people who are curious about the universe and are not primarily interested in how meticulously accurate they can make the instrument.

"For our group," says Russell, "the trouble is that *Amateur*

Telescope Making wants the mirror-maker to reach perfection. Now what does a truck driver- or a lawyer-know about paraboloids? He asks: 'Must I become a mathematician or am I making a telescope?' The major fault with all the mirror-making manuals is the tacit assumption that the aspirant with a disk of glass in his hands for the first time must achieve perfection, or else the telescope is not going to work, when the fact is that practically any mirror will work so well that the average beginning observer will not be able to distinguish the best from the worst. All the telescopes work, and their makers are tickled to death. True, under the Foucault test the mirror may not look good to an expert, but we have made a friend, the friend has made a telescope, and we have promoted interest in astronomy. A few do make really fine mirrors but ironically the payoff comes when they discover that these show no more than the one made by Joe, who has never even seen the book.

"We have found that a man or woman who consumes too much time on what seem unimportant details gets discouraged and quits, even giving the mirror the famous fireplug treatment described in the book-slam it against the nearest hydrant, brush off your hands and go home. (In fact, we keep a private hydrant handy in our laboratory.) For the first mirror, after making sure that the beginner has not even opened the book (copies of which we keep locked up) so that he does not become aware of the many pitfalls, we instruct him from the blackboard and at the bench while he works. We allow each student to proceed according to his individual ability.

"We had to abandon Pyrex, the mirror handle, the paraboloid and the pitch polishing lap. For pitch we substitute wax honeycomb foundation (HCF) used with cerium oxide. Although pitch laps give better polish and fewer zones, they are so difficult to make and to alter that we regard them as the principal bottleneck in mirror-making. They have discouraged more beginners than any one thing, or any 10 things. Although we get fewer fine mirrors with HCF, it best suits our purpose, which is to finish a mirror while the maker's enthusiasm lasts. Moreover, an HCF lap does not scratch. One could almost toss a handful of mud on one without causing scratches; sometimes, as a demonstration, I actually do toss in cigarette ashes. With 50 people milling around in our big room, stirring up dust, HCF is an ideal material. We buy it by the crate. And where it takes half an hour to perfect a pitch lap, an HCF lap takes but four minutes.

"Our objectives on the first mirror are to teach the essential technique and to produce a mirror of tolerable rather than perfect quality. We don't permit as much as a single squint with the testing apparatus until the polish is clear to the edge. Each student must also make a simple tester, take his mirror home and work there with it until he can read the Foucault shadows. Some become expert. Others who do not catch on are also unlikely to know bad images from good at the telescope eyepiece, so this problem takes care of itself. If the beginner is uncommonly apt, he may be permitted to finish on pitch. If he is uncommonly inept and begins to falter even with our simple technique, or is seen to be striving too hard for perfection, we tell him his mirror is good enough and to put it into use.

"At the conclusion we tell them: 'Now read *Amateur Telescope Making*, see what you did and, with its instructions and the orientation you gained by going through the work once without it, go ahead with the larger telescope you want to make. 'The initial aim, however, is to complete a pilot job on mirror and mounting. Our mountings are simple and tubeless. We have the precut parts for them, since many of the beginners are not mechanics.

"Because we consider the human angle and help the beginner to bridge the gap between his capabilities and the bookworms' and wizards' book, 80 per cent finish the first telescope. Most beginners don't want to be experts; they just want a telescope, mostly to look at the moon and Jupiter, and they don't care too much if the moon is a little out of shape or Jupiter is fuzzy.

"After climbing aboard by this preliminary 'gangplank' job, some go on to build fine telescopes in our laboratory, up to 18 inches in diameter, also Cassegrainians and Schmidts. *Amateur Telescope Making* becomes their bible."

FOR YEARS there have been debates about whether *Amateur Telescope Making* should be rewritten-to make it not simpler but more orderly. The suggestion always elicits strong reactions from the book's users. The iconoclastic wing demands, in the words of one: "Melt the whole thing down, stir the melt together, and pour it again as a single, coherent casting, the orderly product of a single mind at a single time." On the other hand, there is a stubborn opposing group whose view is summed up in this remark: "ATM has been my companion for 20 years. I like it as it is. It is not to be altered in any respect." To many who say they have read it more times than its editor (who prefers escape from optics into the history of the Dark Ages) and who insist they can rattle off its pages by heart, the idea of melting down this old bible seems almost sacrilegious.

They need not worry. While I see nothing sacred about it, if the book were rewritten it would have but one author and therefore would lose the prestige of its present galaxy of contributors. It would likewise lose Russell Porter's irreplaceable illustrations. Its present arrangement or, rather, disarrangement- the result of many additions and internal operations down through the years- does, as has been said, forbid straightforward reading. However, it encourages enjoyable, informative browsing. In fact, the need for a book for browsing goes clear back to the original thought I had three decades ago while lying abed late one Sunday morning. The dream was to bring together as reprints in one volume all the widely scattered, obscure and fragmentary data on telescope making which, in making my own first telescope, I had been forced to mine out of the four-million-volume New York Public Library, and to make this omnium gatherum of forgotten fragments available to everyone everywhere. The book that resulted was a labor of love, performed out of working hours and with the expectation of financial loss to the publisher for the sake of a gain to the amateur. I did not at all realize in 1926 that I had hold of something which awaited only a catalyzer to start an apparently endless reaction.

Out of a feeling of moral obligation, I invite the views of the amateur telescope-making fraternity on whether they would like to see certain changes in the book; like most invited advice, it will be followed if it is liked.

Some have suggested replacing the Porter and Ellison parts of Amateur Telescope Making with more recent mirror-making techniques evolved by some of the graduates from the same preceptors. Leaving aside the fact that such decapitation of the book would leave meaningless 1,001 cross-references to Porter and Ellison in the rest of the book and its sequel volumes, the question arises: Just which and whose pet -techniques, of which there are today as many as there are advanced amateurs, would the reader select for this apotheosis and canonization? Others have urged that the art of mirror-making should be changed to a plain-sailing science by prepared panaceas for every possible contingency in mirror-making.

Both *Amateur Telescope Making* and its much-admired companion, Allyn J. Thompson's *Making Your Own Telescope*, go into the full depth of meticulous detail for the making of the first mirror. Both imply, as Russell says, that a beginner must set his teeth to produce a perfect mirror. How many isolated beginners, haunted all through by the hobgoblin that the mirror won't work unless it is perfect, have worried themselves to a frazzle through a thousand misgivings, only to find when they completed the mirror that it worked splendidly in spite of its imperfections!

The other side of the argument is that the difficulty of telescope making is what has made it attractive to resourceful and adventuresome people, and that to reduce this endlessly intriguing, baffling and sometimes maddening art to a science, even if this were possible, would rob it of its dark allure. The books tell only half-they could not tell the rest anyway-and the happy sufferer supplies the other half of the answers out of the depths of his resourcefulness and fortitude. The work is essentially a test of character.

Yet must we be so tough, when we can more charitably serve all comers according to their individual capacities? Here is a proposal: Instead of rewriting Porter and Ellison and attempting a general rejuvenation of the venerable ATM (which, in case you are wondering, has suffered no loss in demand), suppose we simply add a crutch chapter based on the Russell approach for all who are panicked by paraboloids. To make space for the chapter, the present instructions for silvering mirrors and the list of astronomical groups (no longer needed because it is kept current in *Sky and Telescope*) could be dropped. The new gangplank to paradise would be placed at the end, partly from sentiment -it must not precede Porter and Ellison -and partly for practical reasons: the book is not printed from movable type but from whole-page plates, and the pagination must not be altered. The preface would direct the beginner to the optional easier approach. This, of course, would afford everyone a bonus in the form of a new opportunity to rib the editor about this "incomparable paragon of reverse sequence."

Next month I will explain in terms of physical optics why even a poor mirror can work, will describe a revised criterion for good mirrors, will show why an experienced observer still needs one, and will tell why even that criterion or the stiffer Rayleigh limit criterion is not good enough for the most expert observing, even though a beginner may not be able to detect the difference between it and any old mirror. From that explanation the reader will see that there is no intention to debase mirror-making but instead to spread out the standard-much looser for some, tighter than ever for others-to make everyone happy.

THE TELESCOPE Makers of Springfield, Vermont, with the Amateur Telescope Makers of Boston, will begin a new series of conventions of amateur astronomers at Stellafane August 21. For information communicate with James W. Gagan, Harvard College Observatory, Cambridge 138, Mass.

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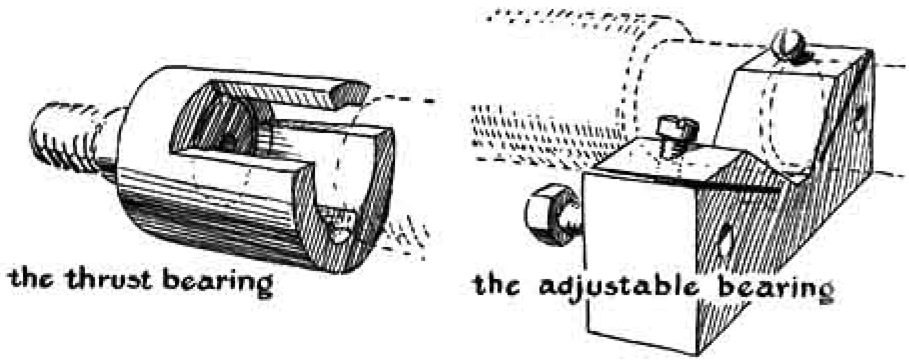
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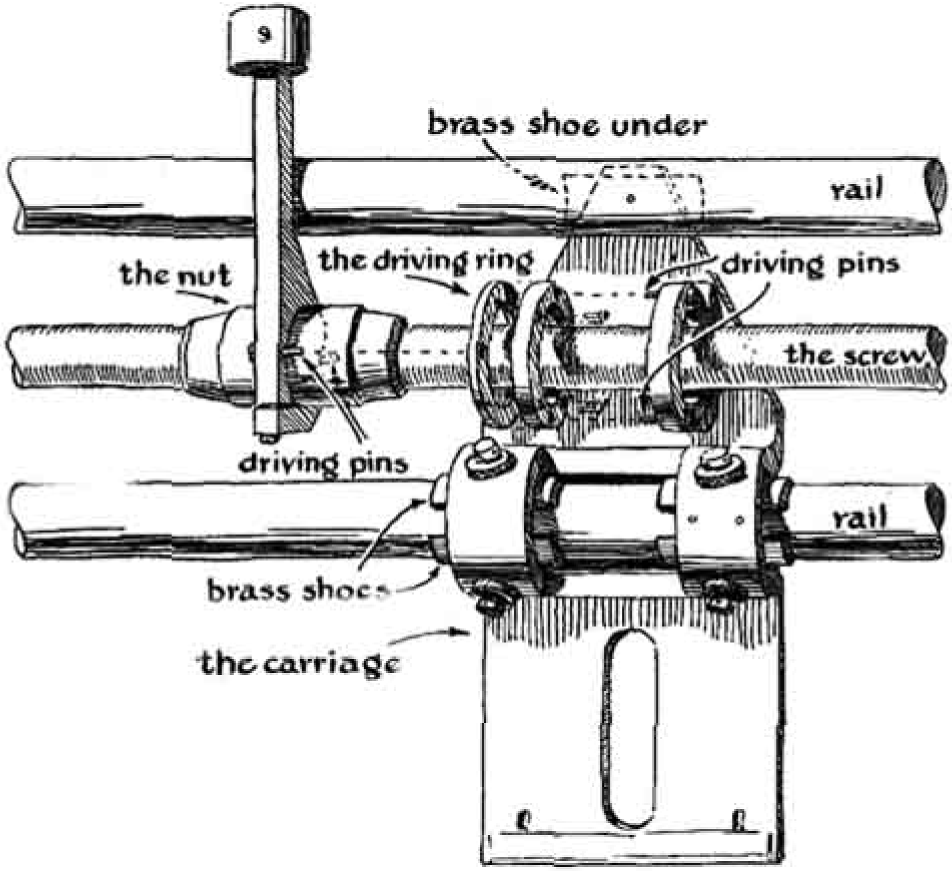
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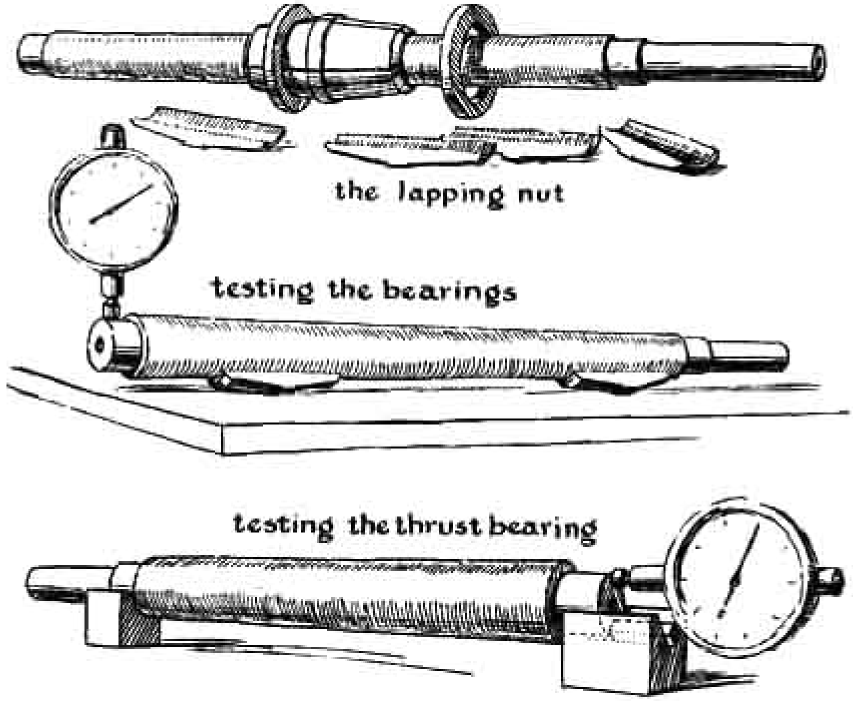
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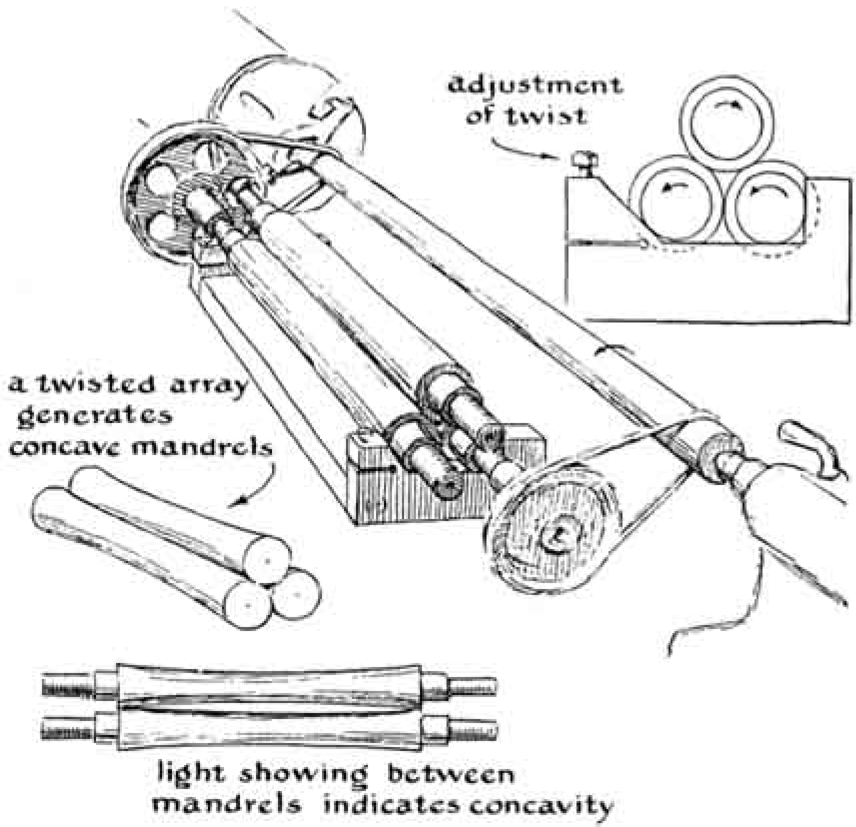
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