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LABORATORY WORK WITH THE SUN

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THE attitude of the sun to the earth is most vital. With the sun high in the sky day after day a warm climate results. With an increase in the length of day, that is, with an increase in the number of hours of sunlight, summer returns to the higher latitude. On a summer day the temperature of the air rises rapidly with the rising sun, and culminates some time after the culmination of the sun; and the coolness of evening becomes very apparent before the sun has set. These things are noticed in a general way in the study of geography and physiography, but it is not often that any attempt is made to make observations quantitative. Crude and simple devices are sometimes provided by ingenious teachers, and very satisfactory results are gained, and a very earnest interest aroused. Sometimes very accurate results are gained by such devices. But more often the limitations of the apparatus offer a real obstacle to any quantitative work, making observations valuable merely in a qualitative way.

The principles involved in taking quantitative observations on the sun are simple. They are not too difficult for the intermediate grades. The circle and its elements; even the sines, tangents and co-tangents, as geometrical relations, if observed, and dealt with graphically, are fascinating to a fifth grade boy. Give him the compasses, the protractor and scale, and put the angles before him to be read, and he will take pleasure in solving many problems. The actual instrumental work fixes the principles in the memory of the observer as no amount of drill on the mere formulas ever can do. To make it possible at a minimum expense, for teacher and student to do the instrumental work, the author has devised a little instrument with the homely name of Sun Board. It is only five inches across, carrying within

its outer rim a movable horizon about three inches in diameter. Upon this

horizon is a doorway an inch high thru which the sun may shine. Behind the doorway is a quadrant upon which the sun may cast the shadow of the top of the front board, so making it possible to read the sun's altitude direct. Thru the horizon a diameter with a scale alongside is etched from the middle of the doorway so that shadow lengths may be read upon the horizon. Three leveling

screws beneath the frame of the instrument, and a plumb line hanging in front of the doorway, make it possible to establish the horizon. Opposite the doorway a hinged beam box makes it possible to read from a scale the power of a sunbeam in heating the surface upon which it falls.

Several other relations may be demonstrated with the instrument, and it may be worth while to make a list of its uses, and to suggest a number of problems which may be solved by its use.

1. *To Establish the Horizon.* Put the Sun Board upon the window sill, or floor, or some firm, approximately level surface, and adjust the level by the three leveling screws. The level will be established when the plumb line rests in the middle of the hole in front of the doorway. This hole is only about two millimeters in diameter, so the adjustment is close. The principle involved here is that a level surface is at right angles to the "line of direction," and the line of direction is the path taken by a falling body, or by a string hanging freely and supporting a weight *e. g.*, the plumb line. The plumb line is then a line vertical to the established horizon.

2. *To Read the Sun's Azimuth,* (or angular distance from the south point). In meteorology all positions in the horizon are read in degrees from the south point around by way of the west. West is thus 90° , north 180° , east 270° , and so on.

Place the Sun Board with its south and north points in the meridian, which, for the present exercise, may be determined by means of a compass. Turn the movable horizon until the doorway faces the sun, and watch the shadow of the plumb line as it falls under the doorway. When this

shadow coincides with the scaled diameter crossing the horizon of the instrument, the doorway end of this diameter gives the reading of the sun's azimuth, on the graduated circle on the stationary frame of the instrument. The plumb line being vertical, may be considered as an element in a vertical circle, and when its shadow coincides with a diameter of the movable horizon, we have located the vertical circle passing thru the sun and the zenith. The angle in the horizon between the south point and this vertical circle, is the azimuth. A vernier limb is engraved upon the movable horizon making it possible to read the azimuth to 15 minutes of arc. Any time in the day, then, from sunrise to sunset, azimuth may be read with great ease. But a meridian established by a compass is not reliable. One cannot be sure that it is true.

3. *To Establish the True Meridian.* Where is the south point? This seems an easy question, until we look it squarely in the face. We may fix the meridian with more or less accuracy in several ways:—

(a.) We may locate it with a compass, if the compass is accurately made, and if it is not influenced locally by iron or steel objects. But the compass needle does not point to the true north except along the line of no variation, which in this country runs near Detroit, and Charleston, S. C. The observer needs to know then the exact amount the needle varies from the true north in his locality. This is very hard to find, for when an approximate value is taken from the chart of magnetic variation, there are in many places rather large local variations, a fact which puts our compass readings in some doubt. Then too, the variation for our locality as found, must be dated because a slow change in the value of the magnetic variation is in progress, adding another uncertainty to the list. So the compass is far from being a satisfactory means of establishing the true meridian.

(b.) Given an accurate clock or watch, we may set it at the time of sunrise or sunset, as given in the almanac, and so establish our meridian by the shadow of a vertical stick at the instant of noon by the clock. But a number of errors may enter here. For example, the sun's disc covers an arc of about half a degree and the true instant of sunrise is when the center of this disc crosses the horizon. An ordinary observer must guess at this instant, or he may take the instant the disc first appears, and make a correction for the semi-diameter of the disc. This is not a serious error. It would make a difference of less than a degree in the true reading of the meridian. Again the times of sunrise and sunset are given in the ordinary almanac for only two or three latitudes in our whole wide area. If the observer does not live in these particular latitudes, errors of judgment are

certain to enter, and the possibility of error increases with the increase in latitude. And again a much greater possibility of error confronts us, in that the sun crosses the meridian at the clock noon, it may be, only once in the year, and on only four days in the year will it come within six or seven seconds of it. On all other days the sun will be either faster or slower than the clock, the maximum error being over 16 minutes. So one must refer again to a table in the almanac to find the exact time at which the sun crosses the meridian on the day the observation is to be made.

(c.) With the Sun Board the problem is very simple. If we can install it where we may take azimuth readings at sunrise and sunset, we may divide the horizontal angle between these two readings, and have our true south point. For this first determination, the instrument may be put down in any random position, so far as concerns the point upon it marked "south," for all one needs to do is to get a reading for the horizontal angle between these two points. When the reading of the midpoint between sunrise and sunset has been found, still being careful not to move the instrument, rotate the horizon, to bring the zero of the vernier limb, to this reading. Now the plumb line, and the vertical wire in the beam box, (when the box is in the horizontal position), will serve as two sights, to control the erection of two pins or wires which may be driven into the floor or window sill, and between which a permanent line may be drawn, as the position of the meridian. This position will be true to within fifteen minutes of arc.

It is not absolutely essential to have the Sun Board in the sunlight at sunrise and sunset. It may be put in any south window and the meridian determined as follows: Take an azimuth reading in the forenoon, when the sun has a given altitude, say 45° (see problem 6, below), and then take the azimuth reading in the afternoon, when the sun has fallen again to an altitude of 45° . The midpoint between these two readings, is the south point, and the meridian may be established as above described.

It will be noticed that this is the *true meridian*. The sun will cast its shadow on this line, at noon by the clock on only four days in the year, even if the clock is keeping 'sun time,' because solar days are not of uniform length, as the clock days are, being longer at perihelion and shorter at aphelion. And this difference, very seldom thought of, perhaps even ignored in our teaching, may be illustrated and made plain by actual measurement with the Sun Board.

4. *To Make a Graphic Construction of the Time Equation: The Analemma.* The period of the earth's rotation is about the most perfect

unit of time measurement known. To measure the length of this period one must take a base of reference on some object outside of the earth. And here trouble begins, for a dual opportunity of reference presents itself; we may refer to a star, taking the period between two successive appearances of this star in our meridian, and we have what is called the "sidereal day," a period which is uniform, day after day thru the year. This is the real basis of our system of time. But the determination of this day is difficult to the ordinary observer, tho a relatively simple matter in the astronomical observatory. The other method of measuring the period of rotation is most obvious, but gives a variable result, and lays us liable to serious difficulties in the time measurement; this method takes the sun as the extra-terrestrial point to which the earth's rotation is to be referred. The period intervening between two successive crossings of our meridian by the sun, is the solar day, and its very obviousness has forced it upon us as the ordinary unit of time measurement. But the length of this period is quite variable thru the year, being longer in our winter and shorter in our summer. Now it is in the nature of our clocks to keep a uniform rate of time, and we should have to be setting our clock every day in the year, sometimes slower, sometimes faster, to keep it with the sun. This on the face of it would be intolerable, and the easiest solution of the difficulty is the adoption of an *average*, or *mean solar day*. This is the period which, subdivided, gives us the hour, minute and second. The year, and all other duration is measured in this unit or its derivatives.

The graphic illustration of the difference between the sidereal day and the solar day, will make it easy to understand the difference between the solar day and the mean solar day. If an observer A, starts say Jan. 6, with

the instant the sun is in his meridian, s-s, to measure one earth's rotation, he will have passed thru 360° of arc, when he has arrived at position A in the plane S'-S' on Jan. 7. This is the measure of the sidereal day, the star being so far away that its rays are practically parallel at all parts of the earth's orbit. In the diagram this is shown, by making S'-S' of Jan. 7 parallel with S-S of Jan. 6. But the observer at A on Jan. 7 is not yet at noon, because in the one rotation the earth has traveled forward in its orbit about one degree, represented in the drawing by S'OS, and the observer

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must travel on over the arc AA' , before he has the sun again in his meridian. This longer arc, which as we see, is about 361° of rotation, is the solar day. Now if the earth's orbit were a circle, and its rate of travel in this orbit were uniform, this longer arc would be uniform, day by day, and would give us as uniform a period as the sidereal day. Under these conditions a clock running with a uniform rate might be set by the sun, and stay with it all the year. But the earth's orbit is an ellipse, and the earth, for six months, from aphelion (A) to perihelion (P), is a falling body, coming closer and closer to the sun, and increasing its linear velocity as a consequence. So that in a unit of time, it passes over a considerably longer arc and larger angle in the region of the perihelion, (*e. g.* aPb) than it does six months later, at aphelion, (cAd). Thus in a sidereal day at perihelion a longer arc of orbit is passed over, and a larger increment of time must be added by the observer to bring him to his meridian, than is the case at the aphelion. Thus in the perihelion part of the year the clock noon arrives before the sun crosses the meridian, and the sun is said to be 'slow.' Again at aphelion the mean solar day is a little longer than the actual time between meridian transits of the sun, and the sun comes to his meridian before the noon of the clock, and the sun is said to be 'fast.' A little consideration will show that the mean solar day must be a trifle longer than the shortest solar days at aphelion, and somewhat shorter than the longest solar days at perihelion.

Thus there will be four times in the year at which the sun will coincide with the clock, being alternately faster and slower than the clock in the intervals. To establish this relationship we have the time equation. To observe it and chart it graphically is our present problem.

With the Sun Board in place, *i. e.* the scaled diameter accurately in the meridian, take the time at which the shadow of the plumb line lies in the meridian. Set down this reading as so many seconds or minutes before, or after the clock noon, as the case may be. Take as many readings as possible

thruout the year, and enter them in a graph, as follows: Draw a right

line AB which shall stand as the earth's orbit, making it $365\frac{1}{4}$ units long, for the days of the year. This line may be laid off on cross ruled paper, and the months with their days indicated. Then enter each observation at its proper day, as a line at right angles to this base line, with a value expressed in convenient units; for example giving the ordinate of sun's error a value equal to the space covered by five days on the year line. Let all 'sun fast' observations be "+" and entered above the line, and all 'sun slow' observations "-" and entered below the line. When the year's record is complete, connect the termini of all these sun's error lines with a smooth curve. The dates of the intersection of this curve with the line A-B, are the dates when the sun time and clock time coincide. These dates are about April 14, June 15, Sept. 1, and Dec. 25.

The observations for this study may be made any convenient day, and the sun's error entered for the record, tho one would wish to have more frequent observations at the time of the sun's maximum departure from the clock time.

The time equation is sometimes graphically shown in the form of a figure 8, called an analemma, which one may see and study, on a good globe.

So far in this problem we have assumed that the clock was keeping local time. But many people, perhaps most people in America do not now set their clocks by the sun. They keep standard time instead. Of course for all people living on a standard time meridian the above instructions apply, because standard time for them is their own local time. But if the observer live at one side of the standard time meridian, there is a correction for his longitude to be remembered and applied. This leads us to the next problem:—

5. *To measure the difference between local or sun time, and standard time.* Install the Sun Board in the true meridian. Rotate the movable horizon, bringing its scaled diameter into the meridian, with the plumb line at the south point. The sun now will cross the meridian when the shadow of the plumb line falls in this diameter. If, now, the clock or watch used has the correct standard time, the observer will note carefully the exact time the sun crosses the meridian. Let us suppose the observer to be at Green Bay, Wis., and that he makes the observation on Jan. 10. He finds that the shadow of the plumb line falls in the meridian at eleven o'clock 23 minutes and 32 seconds: that is, 36 minutes 28 seconds before the noon of standard time. Referring now to the time equation he finds the sun on Jan. 10, 14 minutes 28 seconds fast. Subtracting this 14 minutes 28 seconds from 36 minutes 28 seconds leaves us 12 minutes, a difference which standard time brings to the reading. Since this 12 minutes shows the clock

to be slow, the observer may know that he is east of the meridian from which his standard time is reckoned. And since one degree of longitude is equal to 4 minutes of time, dividing this time difference by 4 will give him his longitude difference; $12 \div 4$ equals 3° and 3° from 90° equals 87° west, the observer's longitude.

6 and 7. *To measure the sun's altitude.* Place the Sun Board in its meridian as before, and rotate the inner horizon, so as to face the doorway toward the sun bringing the shadow of the plumb line into the scaled diameter, so establishing the sun's azimuth. The sun will be shining directly into the doorway, and illuminating the scale of degrees making it possible to read the angle of the sun's elevation. This is a very convenient scale for altitudes between 20 and 60 degrees, but for angles higher than 60 the degree spaces are too small and in the nature of the case the angles below 20 cannot be read. An alternative and superior method of taking the sun's altitude is provided in the vertical quadrant behind the doorway. This reads all angles equally well from the horizon to the zenith. The rear edge of the top of the door frame runs thru the center of curvature of the quadrant and the sun shining across this line, casts the shadow of the doorway upon the quadrant. The angle left illuminated reads the sun's altitude. The small size of the instrument gives it a decided advantage in this reading, for the scale where read is only an inch and a half from the top of the door frame which casts the shadow. This reduces to a minimum the error due to diffraction, giving an opportunity to read to an estimated fraction of a degree.

Another way in which the sun's altitude may be studied, is found in the linear measurement of the shadow of a vertical post. The doorway serves the same purpose here, and a scale is provided in inches and twentieths reading from a zero point in the front surface of the doorway. So one may read this shadow length at noon, on random days thru the year, watching it grow very short when the sun is at a high altitude at noon in June, and then increasing in length day by day until its farthest reach on the winter solstice, Dec. 21st.

Another interesting study may be made, of the altitude of the sun, hour by hour through the day. The very rapid change in altitude in morning and evening, and the extremely slight change in altitude during the middle of the day, have a very close relationship to the daily range of temperature, which may be worked out graphically. For the heating power of the sun is a function of the sun's altitude. This special problem is taken up under Problem 9.

8. *To determine the latitude of the observer.* On the day of the

equinox the sun's vertical ray is on the equator, and the poles have tangent rays. At noon on this day the sun's altitude all over the earth, is the complement of the latitude of the observer. For example, at latitude 30° the sun will have an elevation of 60° at noon; and $90^\circ - 60^\circ$ equals 30° , the observer's latitude. On this day, then, any observer, reading the sun's altitude at noon, may subtract this reading from 90° and have his latitude.

At the other critical dates, the solstices, the problem is also easy. For at the summer solstice the sun's vertical ray is $23\frac{1}{2}^\circ$ farther north than at the equinox, so from the sun's altitude at noon, one subtracts $23\frac{1}{2}^\circ$, and then proceeds as before. For the winter solstice one adds the $23\frac{1}{2}^\circ$ to the noon elevation before subtracting from 90° .

It ought to be noted here that there are two solutions of the problem when the sun's elevation is $66\frac{1}{2}^\circ$ or over. For example if the sun's noon altitude is 80° , the solution given above is followed if the sun is on the equatorward side of the observer: $80^\circ - 23\frac{1}{2}^\circ$ equals $56\frac{1}{2}^\circ$; $90^\circ - 56\frac{1}{2}^\circ$ equals $33\frac{1}{2}^\circ$, the observer's latitude. But if the sun is on the poleward side of the observer, he must subtract the complement of the sun's noon altitude from $23\frac{1}{2}^\circ$ for his latitude. Thus: $90^\circ - 80^\circ$ equals 10° ; $23\frac{1}{2}^\circ - 10^\circ$ equals $13\frac{1}{2}^\circ$, the observer's latitude.

Of course for any intervening day, between equinox and solstice one may consult the ephemeris, or one of the larger almanacs, and find the altitude which corresponds with a given day. Or one might make his own table by constructing a projection of the path of the vertical ray, making it possible to read directly from this graph, the sun's declination for any day in the year. To construct this graph lay off on a right line a distance A-B which shall be 365 units long, for the days of the year. Di-

vide this line into quarters. With one quarter as a radius, and with a center at c, strike the semicircle AGd, and with e as a center the semicircle

dFB. This radius cG is then divided into $23\frac{1}{2}$ units beginning at c, and the same with eF beginning at e. These divisions are for the latitude degrees covered by the sun's vertical ray. Thru these degree points lines are now drawn parallel with AB to cut the circumference of the semicircles. Now consider point A the autumn equinox, c the winter solstice, d the spring equinox, e the summer solstice, and B the autumn equinox again, and lay off the calendar on the line AB, showing the days of the month at the day spaces, and drawing ordinates or vertical lines through the day points to cut the semicircumference below or above the line as the case may be. One now reads the sun's declination for a given day, as for example Oct. 1, by reading the degrees indicated on the day's ordinate gh. And in the Northern Hemisphere this reading would be added to the sun's altitude at noon on Oct. 1, before subtracting from 90 to find the observer's latitude.

The year having 365 and *one-fourth* days this construction will not give strictly accurate values, tho they will be quite close enough for purposes of laboratory exercise.

9. *To show the relation between the sun's altitude and its heating power.* Leaving the influence of the atmosphere out of account, the sun's power in the production of heat, varies inversely as the surface covered by a beam of given cross section. This area covered bears a simple relation to the angle of the incident beam. A vertical beam has the maximum efficiency, for here it is concentrated on the smallest possible surface. As the beam is inclined it covers a larger surface, so the unit area receives less energy. For instance, at an elevation of 30° the beam, covering twice the original area, (Fig. 6, OB equals 2OA) will give to the unit surface only one-half the energy which the vertical beam would give. This principle is

taken advantage of in the beam box of the Sun Board, and the scale provided with it. For this determination the Sun Board may be placed in the sun anywhere, without reference to the meridian, and leveled. Then the horizon is rotated to bring the beam box toward the sun. The beam box is now rotated on its hinge until the two cross wires in the box, which are parallel with the hinge, bring their two shadows into coalescence upon the movable horizon. This assures the proper altitude of the box. Now rotate the horizon until the cross wire in the box which is at right angles with the box hinge, casts a shadow into the scaled diameter on the movable horizon, and the sun's azimuth is found. These two adjustments put the beam box into coincidence with the sun's beam.

The box has a cross section of a square half inch. Running along the en-

graved diameter, is a scale of half inch units, divided into tenths, and reading from a zero in the hinge line of the box. Thus when the box is vertical its inner surface encloses just a square half inch of the horizon. When it is inclined, the sun shining thru it illuminates the movable horizon, and the area covered by the beam can be measured exactly in units and tenths from the part of the scale illuminated.

The intensity of insolation is thus read arithmetically in terms of the efficiency of the vertical ray, as the reciprocal of the scale reading. Thus if the beam covers 2 scale units the intensity is $1/2$. If it covers three scale units, the intensity is $1/3$. If the reading is 1.3 the intensity is $1/1.3$ and so on.

An exercise may now be set to show the heating power of the sun for all the hours of a given day. The readings may be taken with the Sun Board on each even hour, the observations recorded in a table, and the table then converted into a graph as follows:—On the cross ruled paper lay off a line

of convenient length, AB, which is divided into equal spaces for the hours of the day. Number the hours each way, from the mid-point, which is 12, noon.

On the noon ordinate, (12C) lay off a convenient unit (12D) for the heating efficiency of the vertical beam. In this unit the insolation of all inclined beams will be expressed as fractions. These fractions, the reciprocals of the scale readings converted into simple or decimal form are the natural sines of the sun's elevation, and are to be laid off each on its respective hour ordinate. Connect these points and the sunrise and sunset points, and we have the graphic record of the insolation for each hour of the day. The area of the figure AEBNA is the sum of the total day's heat receipt, which can be expressed in any convenient unit of area.

It will be an interesting and very valuable exercise, to make such figures for a series of days chosen at critical dates thru the year: For example at summer solstice, equinox, and winter solstice. Fig. 8 shows how three such graphs of heat receipt might look. The comparison between them will be easiest expressed in a common unit of area, say the square of the cross ruled paper, enclosed by the curve (SNE) limiting the reciprocals of the hourly readings. In this case these numbers are 212, 122 and 36. One cannot look at these three graphs without seeing why there is a warm season and a cold season.

Such "daily heat receipt" graphs may be made for various days thru the year, and the area of each expressed in a numeric. These numbers may

then be built into a graph which will show very accurately the accumulation of heat of our summer, and the waning heat receipt of winter. On the same paper with the record of heat receipt, we may enter day by day the temperature of the air. The average daily temperature is the best to use for this, tho a reading taken at eight or nine in the morning will serve admirably. This graph puts before our eyes the real proximate cause of the change of season, expressed quantitatively, and accompanied by an actual temperature record of the results of a variable heat receipt.

SOME RESULTS OF SUN OBSERVATION IN THE FOURTH SCHOOL YEAR

"From observation children should be able to conclude: 1. Warmest part of day when sun shines from most directly above by comparing with morning and evening temperature. 2. Warmest season of year when sun rises highest in heavens during daily track by comparing sun's shadow observations. 3. Warmest parts of earth would be where sun shone most directly upon the earth during the year."