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by

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EXPERIMENTS LEADING TO THE DEVELOPMENT OF AN INSTRUMENT FOR THE MEASUREMENT OF THE QUANTITY AND QUALITY OF RADIATION IN ANY HABITAT.

W. R. Sawyer.

(Interim Report. Not intended for publication.)

The immense importance of the light factor as affecting plants and animals is now much more generally realized than it has been in the past and this has lead to an urgent need for a means of measuring radiation in the field and under water. Many instruments have been designed or adapted, for this purpose. Some of these have proved to be quite efficient as far as total visible radiation is concerned, and also have yielded data on the three main divisions of the visible spectrum. One instrument devised by Klugh in 1927, gives data on the total ultra-violet and extreme violet. No other instrument has been developed for the measurement of ultra-violet in the field and under water. The further the effects of light of different spectral quality is pushed, the more we realise the fact that these different wave lengths have very different effects. Thus, measurements of total radiation may have some significance in the open on land but under water they have very little significance, owing to the selective absorption of the medium. The same is true in the case of forest habitats. If, therefore, we are to secure really significant data it is absolutely necessary to develop an instrument which will give us data on the intensity of each narrow region of the spectrum, including of course both visible and ultra-violet.

Realising the above fact we have devoted a great deal of time to the development of such an instrument and we believe from the results already attained we are within sight of our goal.

In developing such an instrument we have the choice of two types, namely, an instrument in which the regions concerned are isolated by:
1. filters
2. a prism or grating.

The first type has the following advantages over the second:
1. compactness.
2. ease of construction
3. ease of calibration
4. ease of reading
5. comparatively inexpensive
6. very robust for work in the field.

Many instruments of this type have been developed and there is considerable data on the three main divisions of the visible spectrum. The best isolation we can get with filters is approximately 1000 Angstrom units. In my report last year under Sources of Error I described the errors due to the antagonistic effects and stressed the necessity for eliminating these. Unless we isolate the radiation into smaller bands than 1000 A, we do not eliminate this effect. To do this, we must use the second type mentioned above, which really means adapting a spectrograph for work in the field. In doing so, of course, we sacrifice the six advantages outlined above.

Before proceeding with the experimental, it might be advisable at this point to define certain terms which will be used frequently in our reports on "light work". The nomenclature and definitions used are those adopted by the O.S.A. Progress Committee 1922-3 on Spectrophotometry. This terminology used is largely in accord with that adopted by the Illuminating Engineering Society. Terms used in "light work" are very badly misused and unless one defines his terms as one goes along considerable ambiguity may arise. Therefore I will define in one place most of the terms which are used in any general discussion on "light work".

"Spectrophotometry may be defined as the visual measurement of relative radiant energy as a function of wave length or frequency.

Radiation is the process by which energy is propagated through space the possibility of propagation being unconditioned by the presence of matter (although the speed and direction of propagation, as well as the amount of energy transferred, may be thus affected.) Strictly speaking the term should not be used to express the thing radiated, as is often done in expressions such as radiations of certain wave length or radiations transmitted or absorbed."

However radiation is used very frequently as the thing radiated in spite of the above definition. It is an analagous case to that of our use of cc. We use cc most of the time when we mean ml in spite of the fact that all our measuring apparatus is marked in millimeters. In my report I will use radiation in the sense it is so commonly used underlining the word when I refer to the O.S. definition.

"For the science or radiation the name radiatics has been suggested. Radiant energy is that which is transferred by radiation. Like any form of energy it may be expressed in energy units, such as erg, joule or (g cal). Radiant power is the time rate of transfer of energy by radiation. Like any form of power it may be expressed in power units such as the watt (or g cal/sec). This term has been internationally designated by the expression *radiant flux*.

If radiant energy be incident upon a surface, the *irradiation* of that surface is the radiant power (flux) per unit of intercepting area. The term *specific irradiation* has also been suggested for this quantity, with irradiation to be defined as the total power incident upon the surface.

Radiometry is the measurement of radiant energy or radiant power; *spectroradiometry*, this measurement as a function of wave length or frequency.

Light is radiant energy multiplied by the visibility of the radiant energy. The time rate of transfer of light is internationally defined as *luminous flux*. Light which is the stimulus should not be used for colour which is the sensation. The expressions ultra-violet light and infra-red light are misnomers.

Table 1. gives the definitions of radiation and illumination in their analogous terms.

Photometry is the science and art of the measurement of light. *Spectrophotometry* is photometry as a function of wave length or frequency, and as already defined serves also in the spectral measurement of relative radiant energy.

There are several wave length units --- the micron u, the millimicron, mu, and the Angstrom, A (0.001 mm = 1 u = 1000 mu = 10,000 A.) All have quite general use, the Angstrom being ordinarily used where there are four or more significant figures. The symbol uu, sometimes called the micro millimeter, has been largely used for the millimicron, but this is inconsistent with the usage of u to denote one millionth.

Radiant energy of a single wave length or frequency actual or approximate, such as is emitted by sources of line spectra or transmitted by narrow spectrometer slits is called *homogeneous*. Radiant energy which is not homogeneous is called *heterogeneous*. Monochromatic has been widely used in the sense of homogeneous as just defined; but the root, chroma, is commonly used in a different sense, as in dichromatic filters, trichromatic vision, heterochromatic photometry.

For the strict definitions of colour, hue, brilliance, saturation, purity, brightness etc. the reader is referred to the O.S.A. Report.

Table 1.

Radiation	Symbols and Defining Equations	Fundamental Units	* Lumination	Symbols and Defining Equations	Fundamental Units	Remarks
radiant energy	E	joule erg g cal	light (luminous energy)	$\int L dt$	lumen-hour	
radiant power radiant flux	$P = \frac{dE}{dt}$	watt g cal/sec	(light) (luminous power) luminous flux	L	lumen	4 lumens are emitted by a source of 1 candle power
radiant emissivity	$\frac{dP}{da}$	watt/cm^2	luminous emissivity	$\frac{dL}{da}$	lumen per cm^2	
radiant intensity	$\frac{dP}{dw}$	watt per steradian	luminous intensity	$\frac{dL}{dw}$	candle = lumen per steradian	
radiance	$\frac{dP}{dwdacose}$	watt/ster^2 /cm projected area	brightness	$\frac{dL}{dwdacose}$	candle/cm projected area =	1 lambert =1000 milli lamberts= 1 candle /cm
irradiation	$\frac{dP}{da}$	watt/cm^2 g cal/cm^2 sec (min) (incident)	illumination	$\frac{dL}{da}$	lumen/cm^2 (incident)	1 lumen/m^2 = lm candle = 1 lux = 0.0001 phot.
radiometry			photometry			
spectro-radiometry			spectro-photometry			

* Logically this term should replace illumination as a name for the science.

EXPERIMENTAL.

1. Spectrograph. We experimented with a Standard Hilger Quartz Spectrograph E 31. This instrument has the following dispersion.

Lengths of Spectra Measures on the plate in cm.
from wave length 8000.

wave length	length	
8000	0	
5000	0.8	
4000	1.5	Total length from
3500	2.1	8000-1850 85 mm
3000	3.0	
2500	4.5	
2000	7.5	

Thus we have quite good dispersion in the region 4000-2900, the ultra-violet region of the sun. The plate used was 4¼ x 3¼. The dispersion is obtained by one Cornu prism.

The first difficulty in using the above instrument in the field was that the plate holder was not tight. We padded it up with velvet and used it last summer, but it was not satisfactory so a new one was designed and has been fitted to the spectrograph.

The second source of trouble was with the slit. For outdoor use when the instrument is pointed directly at the sun, a very small slit width must be used. We tried a number of experiments to determine the most satisfactory and found 14.5 u to be the best. With the type of slit supplied it was very difficult to close it to such a width with sufficient accuracy. With such a small width it is, of course absolutely essential that it should be accurately reproducible, otherwise considerable error will result.

Last summer it was found necessary to measure the width each time by means of a microscope with a micrometer eyepiece. This type of slit has been replaced by one of our own design, which will be tried out this summer.

In order to get as many spectra on the plate as possible, the slit was fitted with a special wedge for reducing the aperture, so that we could get as many as twenty spectra on a plate.

We found that by using short exposure and working quickly we could get along without an equatorial mounting for the spectrograph as well as a planocylindric lens. A slighting device was placed on the instrument and a special holder was made so that it could be readily sighted on the sun. We found that we could use this method without involving another source of error.

Measurement and Calibration

Experiments with a number of different kinds of plates convinced us that the Ilford Process Panchromatic (H. and D. 188) was the most satisfactory for our use. The following developer was found to be the most satisfactory:

Hydroquinone	3 g
Metol	1 g
Na_2SO_3	15 g
Na_2CO_3	15 g
KBr	0.4 g
Water	500 cc

The above are dissolved in order and the whole diluted to one half before using.

We use the following fixer with this:

water	500 cc
hypo	150 g
$NaHSO_3$	15 g
Chrome Alum	5 g

Past experiments have shown the necessity for adhering rigidly to standard conditions of development. With the above method these precautions are very necessary. Various have been proposed, with the object of securing uniform development over the whole plate.

1. Messrs. Ilford have recommended placing the plates in a recess in the false bottom of a developing dish which is very much larger than the plate. The surface of the plate is then flush with its surroundings and forms a small part of a large flat surface. A relatively small quantity of developer is poured into the dish, which is then rocked quite slowly, allowing the whole of the developer to flow right across the plate each time. The false bottom method referred to above is, however, not free from objection. The products of the development are not swept away as quickly as necessary, and the central parts of a uniformly exposed patch are considerably denser than the edges. To overcome this difficulty, the unexposed parts have sometimes been specially exposed afterwards so that when developed they shall have approximately the same density as the images to be measured.

2. Bloch has recommended covering an ordinary "squeegee" roller with soft velvet, the whole of which is soaked in developer, and rolling the plate in various directions with it. The object of this is to remove the layer of developer lying immediately against the surface of the plate, and continually to supply fresh developer to the plate.

3. Dr. Clark of the British Photographic Research Association, has obtained very good results by brushing the plates continually with a wide, soft camel's hair brush during development. This serves a similar purpose as Bloch's roller.

4. It appears that with most methods, the products of development cannot be removed quickly enough from the surface of the plate that their concentration is negligible, i.e. the stirring is not sufficient. If very violent eddies close to the plate, could be produced, more uniform development would result. In this method the following scheme is used. The plates are held in grooves against the vertical walls. A plunger of glass of ebonite, nearly fitting the inside of the tank, is moved up and down within it. There is a clearance of a millimeter between the edges of the plunger and the surfaces of the plates. As the plunger is moved the developer is forced at high velocity between its edges and the plates. Violent eddies are thus produced right against the plates. Above and below the plates are pieces of glass of the same thickness, so that there is no appreciable discontinuity at the top and bottom edges of the plates. The plunger travels a few centimeters beyond the plates, so that the whole is treated uniformly. The velocity of the plunger is kept constant over the whole of its travel. The plunger may be worked by hand or by a heart-shaped cam driven by a motor, the velocity in each case being kept as nearly as possible constant. The plunger travels at a speed of some 20 cm a sec, the developer attaining a speed of about two meters per second past the plates.

5. We found that by using the ordinary developing dish considerably larger than the plate and only filling it about one third full, that providing we adopted standard conditions of rocking, we could get uniformity, and reproducibility, as far as the visual methods of reading which we were using were concerned.

In any method the temperature factor is very important. It is more difficult to control the temperature in 2,3, and 4. We found the most satisfactory way was to use a very small dark room, and to control the temperature of the whole room very carefully by means of a small hot plate.

Special care was taken in washing and drying the plates since with panchromatic plates it is essential to remove all of the sensitizing dye. The slight colour remaining from the sensitizing dye may cause a small error, particularly as the remaining dye will probably be unevenly distributed over the plates. We found the best method of drying after thorough washing was to shake off the excess water and dry in the open.

Another source of error is the non uniformity in the thickness of the film on the plates, due to unevenness of the glass. Sometimes it is necessary to use plate glass, but we found that if the high densities were kept away from, this error in the plates we used was small.

In the case of images whose density is less than about 1.0 most of the silver grains forming the image are situated in the upper part of the film. In this case a small change in the thickness of the film will not greatly affect the density of the image. If, however the image were so dense that the silver grains forming it were distributed throughout the whole thickness of the film, then obviously this part of the film must have too small a density.

Up to this stage it had been found satisfactory to read the plates by eye provided, certain standard conditions were followed. Using such small spectra, we found this method impractical and had to abandon it.

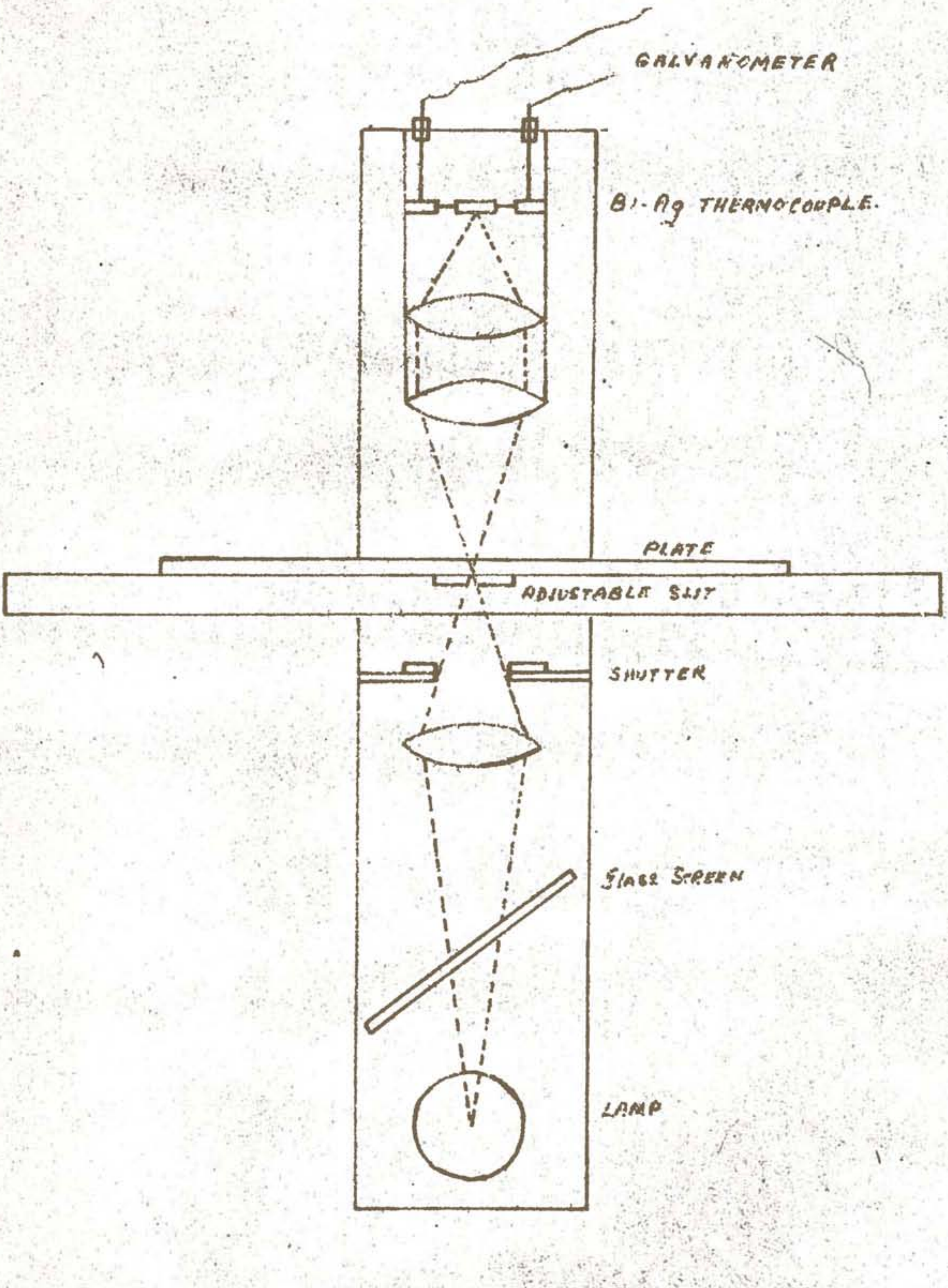
We propose to try the following scheme shown in figure 1.

We expect to have this instrument completed this summer and have ordered a suitable galvanometer to go with it. It is hoped that a slit width as small as 0.1 mm will be able to be used. This will enable us to read very narrow bands of the spectrum. Furthermore we hope to be able to work with a precision of at least 1 per cent.

Standard Plates

The following plan was tried for obtaining the irradiation (g cal/cm^2/sec) at any given point. We chose a given day at noon with a very high radiant flux. Twenty spectra on one plate were obtained, using a constant slit width (14.6 u) and a given exposure. Each spectrum was less dense than the previous one. This was obtained by varying the intensity on the slit by a method to be described later. The first spectrum represented one hundred per cent full noon June sunlight. The remainder were fractions of this from 100 down to 0.1. We could put 10 on a plate and

FIG. 1



GALVANOMETER
Bi-Ag THERMOCOUPLE.
PLATE
ADJUSTABLE SLIT
SHUTTER
Glass Screen
LAMP

use two plates. The fewer the plates the less the error (plate to plate) but the greater the error in matching. Several experiments to obtain the conditions for minimum error have been planned and are awaiting the construction of the densitometer.

We took spectra at various times and places, followed our standard conditions of development and matched in the densities obtained on corresponding wave lengths on the standard plates. This we found very difficult to do by a visual method. We expect the densitometer will settle the question of matching.

Varying the intensity on the slit.

In my previous report I discussed very briefly the methods used for obtaining the variation in the intensity and hence the means of obtaining a standard plate. There are objections to most of them for our use.

The following is a brief review of the methods.

1. Nicol Prisms cemented with glycerine. We found this method most satisfactory. It is described in detail later.

2. Inverse Square Law. This method was used by us last summer using Magnesium ribbon to standardize our plates. If lenses and slits are used this method becomes rather difficult to handle. Obviously it cannot be used with solar radiation.

3. Neutral Wedges. The difficulty here is to obtain a wedge completely neutral to the ultra-violet. A small carbon-in-gelatin or a sputtered quartz wedge has been used, but neither were available for our use. We constructed a wedge 15 cm long, using corex plates, held in place by an ebonite casing. Unfortunately these plates cracked due to the fact that they were not perfectly plane. Carbon suspension in water was used for the wedge medium. The wedge is heavy and requires a special device to hold it in place and move it. Due to the cracking of the plates we were not able to test this as thoroughly as we wished.

4. Punched Plates or Wire Screens in Irregular Motion. This method is certainly not applicable to outdoor use.

5. Sector Wheels. Sector wheels have been used considerably recently. With the Hilger type the intermittancy effect does not appear to cause an error as great as was first thought. Several independent observers have in recent years compared it with other methods, both photographic and photoelectric (Baly, Morton and Riding 1927, Halban 1927, and Gibson 1922.) and it has been clearly shown that there is no difference in the accuracy between the Hilger Sector results and the best of the other methods. This method has been examined very carefully in

the Hilger laboratory in comparison with the polarization photometer, wire grid photometer, and other methods and the results of these tests confirmed those of the above.

We looked upon this method quite favourably but for one point. The sector wheels are made to run in a vertical line and must be carefully levelled. This would mean that in order to use the solar radiation we would require a mirror to reflect it through the sector wheel. Any mirror means considerable reflection losses in the ultra-violet as well as a special calibration. This would be very difficult to obtain in the field. In fact the method as a whole does not lend itself to working in the field.

6. Multiplication of Sources. } obviously ruled out
7. Variation in the Effective Area of the Source. }

8. Solutions of Dyes Obeying Beer's Law. To obey Beer's law seems to be the exception not the rule. It is very difficult to obtain such a dye which obeys the law over a sufficiently wide range to be practical.

9. Variation in Electrical Conditions. ruled out.

10. Oblique Plates of Quartz. These are difficult to handle even in a physics laboratory.

In my previous report I pointed out the danger of calibration on artificial sources to measure solar radiation. All our calibration has been done directly on solar radiation.

1. Method 1 in detail. Since we devoted most of our time to this method I will describe it here in a little more detail. Nicol prisms are usually cemented with linseed oil. This however is not transparent to the ultra-violet so we tried glycerine and found it very satisfactory. We bought two pairs of Nichol Prisms (Glan Thompson type 9 x 9 x 18 mm) and designed a special type of holder for them, so that they could easily be removed and fresh glycerine added. The larger the prisms the less the error due to false light. We obtained the largest we could get and although we are not satisfied with their size, they appear to have given results so far.

The principle of the method is as follows. The radiation is passed through two Nicol Prisms. By adjusting the angle between the principal planes of the two prisms any desired fraction may be transmitted, the amount transmitted being proportional to $\cos^2\theta$ where θ is the angle between the principal planes of the Nicol prisms. Thus for small changes in θ, the corresponding changes in intensity (I) is given by

$$\frac{dI}{I} = 2 \tan\theta \, d\theta$$

and as tan θ increases very rapidly for large values of θ a small error in the setting of the angle produces a large error in the transmitted radiation when θ is large, i.e. when only a small fraction of the light is required to be transmitted. We minimized the above source of error by having quite a large scale for obtaining the necessary angle.

The Nicols were constructed so that they could be held in place on the front of the spectrograph. During the winter an adapter to hold them was placed on the spectrograph.

Data Existing and Data Required

With the instrument as I have described it it is possible to give the irradiation in terms of that existing at the time of the calibration of the standard plates. Since full noon June sunlight changes from time to time and place to place, it would be much more satisfactory to be able to give the data in absolute units (g cal/cm^2//min). If we had the irradiation in absolute units at the time of the calibration of the standard plates, we could then give the data in absolute units of the sources measured.

Unfortunately there is very little of this data available even at the larger observatories. Last summer I brought a Bausch and Lomb Quartz Monochromator to St. Andrews. I intended to use this mounted as we have mounted the quartz spectrograph, to obtain the spectral distribution in absolute units. When the instrument was set up it was found that the galvanometer was out of order. I could not fix it myself, nor have it fixed before the summer was over, so the method could not be tried out. I do not believe this scheme has ever been tried and I see no reason why it should not give the necessary data.

The data on the per cent of ultra-violet radiation is solar radiation is very scanty and not at all satisfactory. We tried to obtain this data at various times last summer. The method was to read the irradiation registered on the pyrheliometer and then place an ultra-violet filter over the thermocouple and read the transmitted radiation. The transmission of the filter to the ultra-violet radiation was obtained by Klugh's Ultra-violet

Photometer. Unfortunately the Corning filter for the ultra-violet transmitted red as well. The ratio red: ultra-violet : 15:1. The red and infra-red were eliminated by means of a copper sulphate cell and the transmission of the whole determined.

The chief difficulty in this work was the fact that the first galvanometer that we used was not sufficiently sensitive to give an accurate reading when the ultra-violet alone was being received by the thermocouple. We ordered a more sensitive one from France but it did not come up to the specifications and was very little better than the former one. However, we have ordered a very sensitive galvanometer and shunt, which we intend to use with the pyroheliometer and densitometer. Corning have also brought out new ultra-violet filters. With the improved combination we hope to obtain the above data on the ultra-violet component of solar radiation. In addition we hope to obtain considerable data concerning the effect of humidity, haze, and clouds on the solar radiation.

Data giving the irradiation on land under various conditions of time and place is unsatisfactory enough, but under water data especially on the ultra-violet is worse still. Even in the laboratory agreement of results on pure water has not been attained.

Hulburt (1928) has recently done some work in the laboratory on the transmission of pure water, tap-water and sea-water to the ultra-violet. It looks like a good piece of work but of course it was done in the laboratory and not in situ. His method was very briefly as follows: light source, mercury vapour lamp, concentrated by a quartz lens on the slit of a Hilger monochromator, passed through two quartz cells (2.07 and 0.15) and then on a sodium hydride quartz photoelectric cell, with a quadrant electrometer. He used the following formula.

$$I = I'.10^{-\overset{a}{\cancel{A}}dx}$$

where a is the coefficient of absorption, when x is measured in cm, 10 being the initial intensity and I the intensity after passing through x cm. He stated that at present no records were available on the penetration of ultra-violet radiation into the water of the ocean.
His values on tap-water do not agree with those of Kreusler (Smithsonian Tables 1927 7th Ed. p 207.) Hulburt claims these values are 10 times lower than those calculated from Kreusler's original work given in his paper. Multiplying

by ten and interpolating gives none too good agreement with Hulburt. A third set of values is urgently needed.

In a conversation with Dr. Keys (McGill) he told me that he had a man working on the same problem in the laboratory, on samples of water from St. Andrews. He used a photographic method. He took spectra through about a foot of water and tried to use such intensities as would keep him on the straight line portion of the density log exposure curve for the plates used. The resulting densities were measured on a Moll Recording Densitometer. He stated however that he could not be absolutely certain that his values kept on the straight line portion of the curve. Furthermore he obtained values different to Kreusler and Hulburt.

With our method we hope not only to be able to repeat the work of Kreusler, Hulburt, and Keyes but also to obtain the values in the sea as well. The latter obviously bear no simple relation to those of the former. Further details concerning the construction of the

ECOLOGICAL SPECTROPHOTOMETER

The instrument will probably be known as an "ecological spectrol-photometer". If we follow the definitions given in the previous paragraphs, due to the fact that this instrument will be capable of measuring beyond the visible (down to 250 and up to 800 mμ) we would be entitled to call it an ecological spectroradiometer. However, the former name is probably the better known and most frequently used for instrument of this type, so probably it would be the better means of naming it.

It is unnecessary to relate here the necessary features of an ecological spectrophotometer. I will discuss very briefly a few of the points which have been considered but which require further experimentation.

Size and weight. Any spectrograph is quite heavy and bulky. From our experiments we feel that a type with a larger dispersion would be more useful, so that we can get better dispersion in the red and near infra-red. We have several schemes in mind to alter the spectrograph in such a way that it will be quite compact without loss of dispersion. The material of the case must be chosen with a view to strength, weight and resistance to sea-water.

If we are going to use a spectrograph under the sea we will have to use long exposures. As light conditions change rapidly, it will therefore be essential to have the least possible delay between exposures. This will probably mean a radical departure from the methods used in our other photometers. The question of inside or outside shutters and the electrical connections to the instrument have yet to be settled.

When the instrument is used on land it need not be quite so complicated as that for undersea use. Hence a means of adapting the land machine readily to underwater work is another idea to be considered.

The methods of calibration and reading of the plates require further experimentation.

As the machine will be rather costly to build, we feel that another summer's experimental work will be necessary to complete all the details of design. We hope at the end of the summer to have all the data necessary to build the "ecological spectrophotometer."

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