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RELATIVE SPECTRAL RESPONSE OF PHOTODETECTORS

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RELATIVE SPECTRAL RESPONSE OF PHOTODETECTORS

by

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A preliminary report on the method and instrumentation used to determine the relative spectral response of photodetectors was submitted as the final report (reference 1) of research supported by research grant NGR 21-023-001. In view of the results of this research the Planetary Radiations Branch purchased some additional equipment in order to design and install a permanent set-up for measuring the relative spectral response of photodetectors. The present report deals mainly with the work done in setting up and checking this permanent installation.

INSTRUMENTATION

The optical system combines a double-pass monochromator with a beam splitter (dual beam chopper). The dual beam chopper consists of two two-sector chopper blades (see M8 and M9, figure 1) designed to be driven by a common synchronous motor operating at a speed which gives a 13 Hz output signal from each chopper blade. Both sectors of each chopper blade are covered by front-surfaced aluminum mirrors. The location and synchronization of the two blades are designed to divide the beam received from the reimaging optics (plane mirror M6 and concave mirror M7, figure 1) into two beams of equal intensity making 120° with each other and with the incident beam.

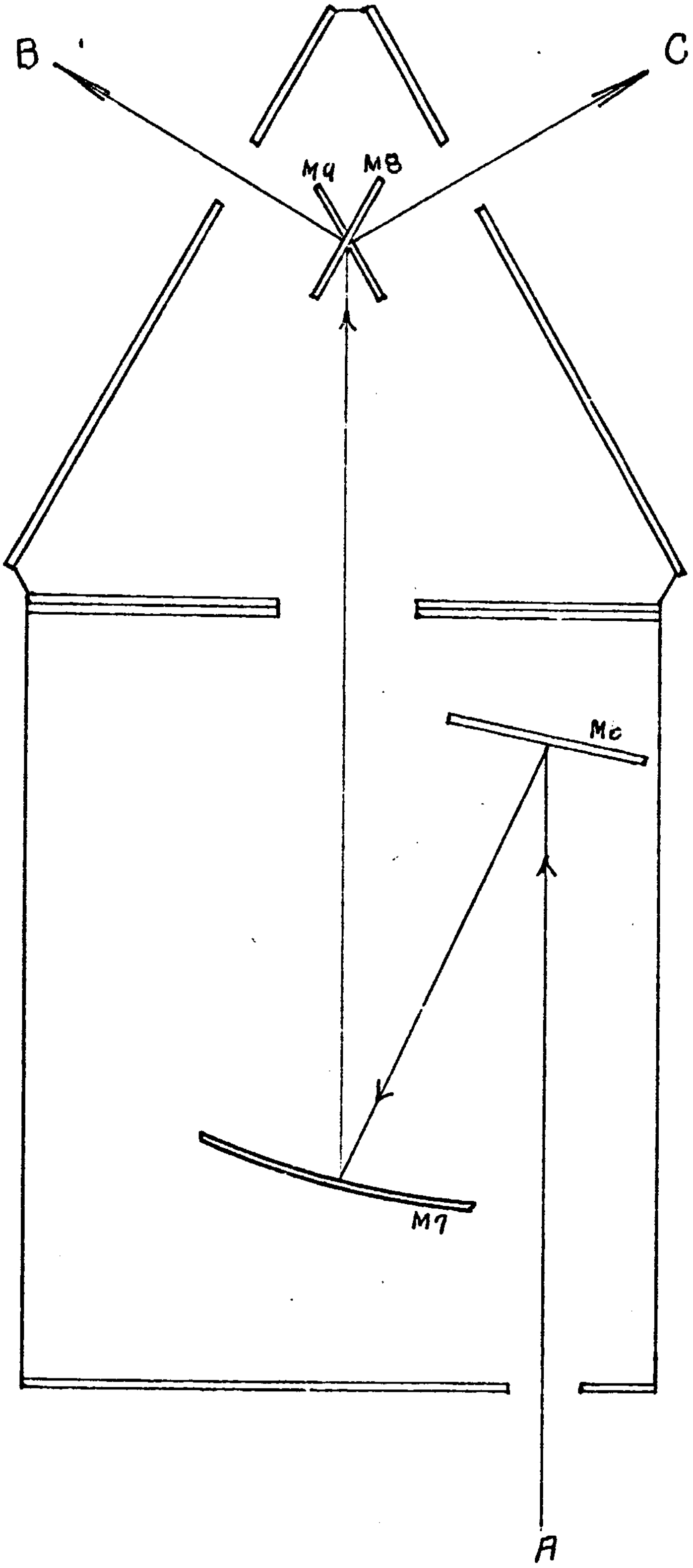

Figure 1. Reimaging Optics and Beam Splitter

Radiation from a source, such as a mercury-xenon arc or a Nernst glower, is focussed on the entrance slit of a double-pass monochromator (figure 2) or a double monochromator (figure 3). This provides radiation in a predetermined narrow spectral band, depending on the monochromator wavelength drum setting and slit width. This radiation is focussed on the exit slit of the monochromator. The emerging beam is collected by the reimaging optics (figure 1) and directed toward the beam splitter (dual beam chopper). The beam splitter then sends one beam toward the reference detector at point B and the second beam toward the detector at point C which is to be calibrated.

In order to position them quickly and accurately, both detectors are mounted on 50 cm long optical benches. In the case of the light reference detector a 50 cm double rod bench is positioned at B (figure 1). This bench is provided with a carriage having lateral and vertical motion, which allows three-dimensional motion in order to position the reference detector at the focal point of the beam at B. The bench located at C (figure 1), however, is a 50 cm lathe-bed type optical bench with a flat bed carriage. This provides a satisfactory carriage for an adjustable support of the heavier radiometer which is to be calibrated.

As reported previously (reference 1), the signal from the reference detector is fed, by way of a remote preamplifier, into a narrow bandpass A. C. amplifier and voltmeter. This meter locks its center frequency to the signal of interest. Since the radiation from the

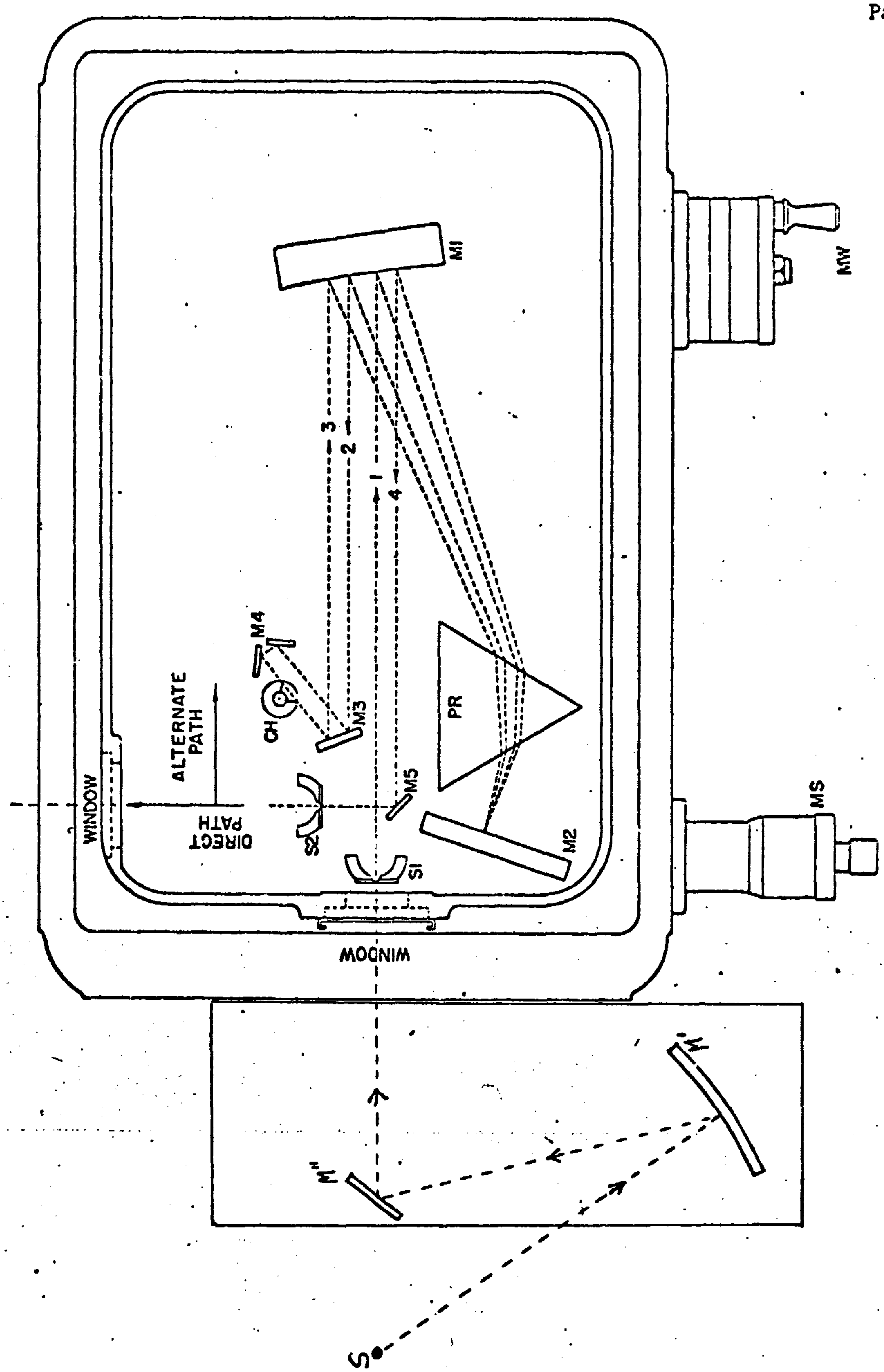

Figure 2. Optical Arrangement of the Monochromator

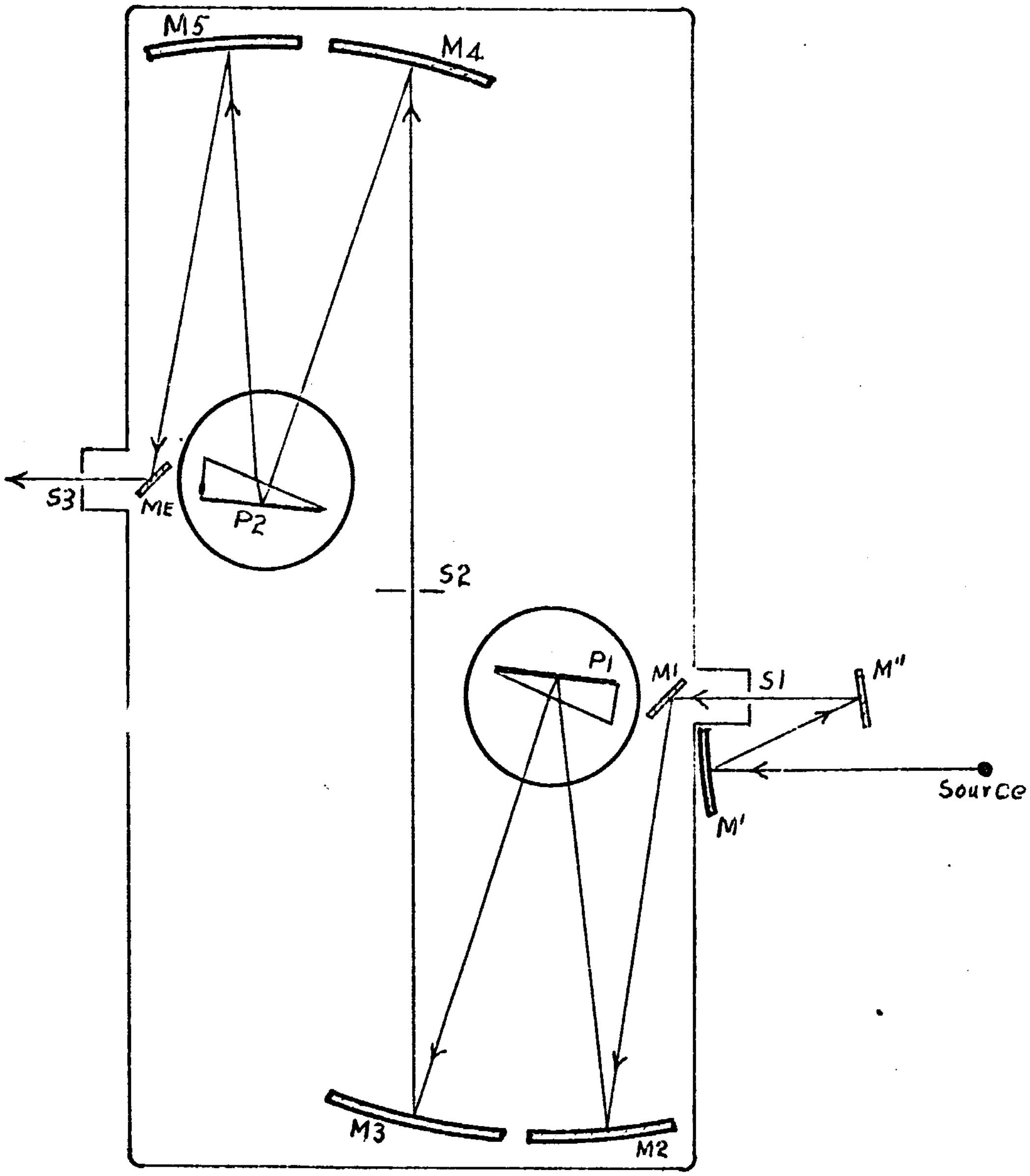

Figure 3. Optical Arrangement of Leiss Monochromator

beam splitter is modulated at 13 Hz, and the lock-in meter is triggered by the same modulator, a high degree of noise rejection is achieved by this voltmeter. After the signal has been rectified by the voltmeter, the output from the reference detector may be read directly on one of the twenty-four full-scale ranges of the read-out meter. Simultaneously a D.C. voltage appears on a pair of binding posts providing an output of 10 volts for full scale deflection regardless of the range used.

Similarly, the signal from the detector under study is fed into a second, but identical lock-in voltmeter. Thus the output of the uncalibrated detector may be read on the appropriate range of this meter. In addition, a corresponding D. C. signal appears on the 0-10 volt outlet.

The D. C. output from each of the two lock-in meters is fed into a ratiometer. This meter has been designed to automatically ratio the outputs of the two lock-in voltmeters. This is possible if the reference input is between 0.1 and 10 volts, and the ratio between the two inputs is between 0 and 1. This ratio may be read directly on a three range meter calibrated to give the ratio of the two incoming D. C. voltages. Alternatively, this ratio may be recorded automatically on an associated chart recorder.

CALIBRATION OF THE PERKIN-ELMER MONOCHROMATOR MODEL 99

After some preliminary measurements had been made with the original set-up, it was noted that the monochromator had to be realigned. This made it necessary to recheck the wavelength of the radiation obtained from the monochromator for any given setting of the wavelength drum. Using customary procedures, the quartz, rock salt and potassium bromide prisms were calibrated by means of both standard line emission spectra and absorption spectra. In the case of the quartz prism, the wavelength drum setting corresponding to the wavelength of each of the standard spectral lines (references 2, 3 and 4) emitted by a mercury arc, and by spectral lamps containing helium, neon, cesium, potassium and cadmium respectively, were determined for the range 0.2 micron to 2.3 microns. In addition, a Nernst glower and nine narrow band pass filters were used for the same range. For the range 2.5 microns to 3.5 microns, standard absorption lines of atmospheric water and carbon dioxide were used. Additional absorption lines were obtained by means of a polystyrene film and a gas absorption cell 5 cm long with calcium fluoride windows alternately filled with ammonia, methane and hydrogen chloride gases and a Nernst glower as the infrared source (references 2, 5, 6, and 7).

The rocksalt prism was calibrated in the range 1 micron to 15.5 micron by using standard lines of the mercury arc and standard absorption lines of atmospheric water and carbon dioxide, polystyrene and ammonia (references 2, 3, 8 and 9). The potassium bromide prism was calibrated in the range 2.7 microns to 24 microns by using the standard absorption lines of atmospheric water and carbon dioxide and of a polystyrene film. In addition, the absorption lines of toluene and 1,2,4-trichlorobenzene were obtained by placing them in a liquid absorption cell providing a 0.05 mm liquid path (references 10-15).

In order to obtain the least-squares curve to fit the experimental data relating wavelength to the corresponding wavelength drum setting for each of the above prisms, use was made of a computer program developed by Andrew W. McCulloch and James T. McLean, Code 622, Goddard Space Flight Center, In this program the computer is required to find a polynomial of degree n, where n = 1, 2, ..., 10, which gives the smallest standard deviation for the measured data relating wavelength to drum setting. The computer is then required to compute and print out in tabular form the wavelength corresponding to each wavelength drum number over the whole range over-which a given prism has been calibrated.

In planning the permanent set-up for determining the relative spectral response of photodetectors it seemed advisable to use a Leiss double monochromator instead of the Perkin-Elmer double-pass monochromator. Consequently, a Leiss double monochromator is on order at the present time. Meanwhile, a Leiss double monochromator with ultrasil and lithium fluoride prisms was obtained on loan from Charles H. Duncan, Code 713, Goddard Space Flight Center. In order to use this temporarily, it was necessary to calibrate it for both sets of prisms.

CALIBRATION OF THE LEISS DOUBLE MONOCHROMATOR

In order to facilitate the wavelength calibration, a slow motion drive was added to the Leiss double monochromator. This consisted of a synchronous motor making one revolution per minute linked to the wavelength drum by means of a plastic positive drive belt and geared pulleys. This reduced the speed of the rotation of the wavelength drum so that it takes 4.78 minutes to complete one revolution.

The standard event marker on the Leiss monochromator operates by mechanically closing a circuit to actuate a relay once for each division on the wavelength drum, hence 100 times per drum revolution. Since this proved unsatisfactory, 20 uniformly spaced .040" diameter holes were drilled in a 5.5" diameter circle on a 6.5" diameter disk. This disk was bolted to the geared pulley attached to the wavelength drum. This made it possible to use an electric eye to close the circuit to actuate the relay of the event marker once for every fifth division of the wavelength drum. In addition, the completion of each complete revolution of the drum is recorded by an additional hole located midway between the first and twentieth holes.

The ultrasil prisms of the Leiss double monochromator were calibrated in the range 0.25 micron to 3.5 microns by means of the same wavelength standards which were used to calibrate the quartz prism of the Perkin-Elmer monochromator discussed above. The lithium fluoride prisms were calibrated in the range 0.28 micron to 6.1 microns by means of standard spectral lines emitted by a mercury arc and by spectral lamps containing one of the following: helium, neon, cesium, cadmium. In addition, the standard absorption lines of atmospheric water and carbon dioxide, and of ammonia, methane and polystyrene were used (references 2, 3, 9, 13, 16). Lastly, for each pair of prisms, the computer program referred to above was used to obtain the least-squares curve to fit the experimental data relating wavelength to the corresponding wavelength drum setting.

The computer program for obtaining the least-squares curve to fit the experimental data relating wavelength to the corresponding monochromator wavelength drum setting was applied to the data obtained for five prisms. Table 1 below is given to illustrate the results which were obtained for the quartz prism of the Perkin-Elmer double-pass monochromator. The table shows the difference between the experimental data and the values calculated by the computer by means of the polynomial giving the least-squares curve. The difference between the experimental data and the corresponding calculated values varies from zero to a maximum of less than 0.21%. As stated above, the computer determined the wavelength corresponding to every drum number in the prisms' range. In comparing the computed wavelength corresponding to every tenth drum number with the corresponding value estimated by means of the best curve which had been drawn through the experimental data, the difference was found to vary from zero to a maximum of about 0.5%. This is better than the accuracy with which it is possible to plot such a curve. Hence it is advisable to have the computer determine the calibration curve by using the data obtained by means of wavelength standards of emission and absorption.

Table 1
LEAST-SQUARES CURVE FIT OF WAVELENGTH AS A FUNCTION OF DRUM NUMBER

Drum Number	Wavelength Lambda (microns)		Delta Lambda	Percent Difference
	Measured	Calculated		
55.0	3.4900	3.4900	0.0000	.000
79.0	3.4405	3.4405	0.0000	.000
100.5	3.3954	3.3954	0.0000	.000
120.0	3.3543	3.3543	0.0000	.000
137.0	3.3171	3.3171	0.0000	.000
159.0	3.2694	3.2694	0.0000	.000
176.3	3.2299	3.2299	0.0000	.000
197.0	3.1836	3.1836	0.0000	.000
211.5	3.1489	3.1489	0.0000	.000
237.0	3.0900	3.0900	0.0000	.000
260.0	3.0320	3.0320	0.0000	.000
281.0	2.9780	2.9780	0.0000	.000
301.3	2.9282	2.9282	0.0000	.000
320.0	2.8804	2.8804	0.0000	.000
348.0	2.8040	2.8040	0.0000	.000
365.5	2.7560	2.7560	0.0000	.000
393.0	2.6800	2.6800	0.0000	.000
417.0	2.6060	2.6060	0.0000	.000
431.5	2.5630	2.5630	0.0000	.000
503.3	2.3253	2.3253	0.0000	.000
525.3	2.2499	2.2500	-.0001	.0004
576.5	2.0581	2.0581	0.0000	.000
598.0	1.9701	1.9701	0.0000	.000
658.0	1.7110	1.7110	0.0000	.000
696.0	1.5295	1.5295	0.0000	.000
708.5	1.4695	1.4694	0.00012	.008
730.0	1.3570	1.3565	0.00050	.037
751.0	1.2434	1.2447	-.00131	.105
775.0	1.1287	1.1270	0.00171	.152
794.0	1.0395	1.0406	-.00110	.106
826.5	0.8944	0.8940	0.00038	.042
837.5	0.8521	0.8521	0.00004	.005
861.5	0.7665	0.7669	-.00042	.055
877.0	0.7245	0.7235	0.00096	.132
899.5	0.6678	0.6692	-.00139	.208

Table 1 (cont.)

Drum Number	Wavelength Lambda (microns)		Delta Lambda	Percent Difference
	Measured	Calculated		
911.5	0.6438	0.6431	0.00069	.107
925.5	0.6153	0.6150	0.00034	.055
945.5	0.5791	0.5793	-.00021	.036
968.0	0.5461	0.5461	-.00003	.005
1000.5	0.5086	0.5086	0.00005	.010
1016.0	0.4916	0.4916	-.00002	.004
1028.0	0.4800	0.4804	-.00039	.081
1042.5	0.4678	0.4675	0.00029	.062
1075.0	0.4415	0.4416	-.00014	.032
1083.5	0.4358	0.4356	-.00016	.037
1135.0	0.4047	0.4050	-.00034	.084
1162.3	0.3919	0.3915	0.00039	.100
1218.3	0.3663	0.3666	-.00028	.076
1232.0	0.3612	0.3611	-.00010	.028
1274.0	0.3467	0.3466	0.00015	.043
1294.0	0.3404	0.3405	0.00013	.038
1313.5	0.3341	0.3341	0.00001	.003
1344.0	0.3256	0.3256	-.00002	.006
1397.7	0.3126	0.3126	-.00005	.016
1417.5	0.3081	0.3802	-.00007	.023
1445.7	0.3023	0.3022	0.00010	.033
1473.3	0.2967	0.2967	-.00002	.007
1495.7	0.2925	0.2925	-.00002	.007
1520.7	0.2881	0.2881	0.00001	.003
1602.0	0.2753	0.2754	0.00008	.009
1641.0	0.2700	0.2699	0.00008	.030
1675.5	0.2654	0.2653	0.00006	.023
1739.0	0.2575	0.2576	-.00014	.054
1777.0	0.2537	0.2536	0.00009	.035
1827.5	0.2484	0.2484	-.00001	.004
1847.0	0.2464	0.2465	-.00011	.045
1864.5	0.2447	0.2446	0.00010	.041
1918.5	0.2379	0.2380	0.00006	.025
1945.0	0.2345	0.2345	0.00004	.017
1975.0	0.2297	0.2297	-.00000	.000

EXPERIMENTAL PROCEDURE

The procedure which was followed was outlined in detail previously (reference 1). Briefly, the monochromator was used to select radiation in a narrow spectral band. The prism chosen for this purpose depended upon the spectral region under study at a given moment. Similarly, a reference detector was chosen in each case based on the transmittance of the detector window for the given spectral region being considered.

The radiation from the exist slit of the monochromator, for a given wavelength setting was refocussed by the reimaging optics and divided into two beams of equal intensity. The two beams were received respectively by the reference detector and the detector being studied.

The output signal for each detector, corresponding to a given wavelength, was monitored by means of its lock-in voltmeter tuned to 13 Hz. The signals from the two lock-in voltmeters were then ratioed by the ratiometer. The resulting apparent ratio as well as the scale range of both meters were recorded. This was repeated at each drum setting.

As a rule the spectral response of the unknown detector is different from that of the reference detector. This means that it may be necessary to change the meter range of one lock-in voltmeter but not of the other. Hence the ratio given by the ratiometer is an apparent one which must be corrected for any change in meter range. Thus the corrected ratio is equal to the product of the apparent ratio time the range of meter A divided by the range of meter B where meter A monitors the unknown detector and meter B monitors the reference detector.

In the preliminary study, the solar channel of the TIROS Five-Channel Radiometer #303 was examined. After obtaining the corrected ratios of this channel output to that of the reference detector, they were normalized by taking the maximum ratio as unity. These normalized ratios represent the relative spectral response of the solar channel of the radiometer over the range 0.3 micron to 4.7 microns.

EXPERIMENTAL RESULTS

The relative spectral response obtained for the solar channel of the radiometer #303 is presented in table 2 and plotted in figure 4. In addition to the experimental results for the solar channel, the theoretical or calculated values of the relative spectral response are also shown in table 2 and in figure 4. The latter were obtained by normalizing to unity the product $R_p R_c T_f R_d$, where R_p is the spectral reflectivity of the radiometer prism, R_c the spectral reflectivity of the chopper, T_f the spectral transmittance of the filter-lens system, and R_d the spectral response of the thermistor bolometer of the solar channel. The data for these four factors were supplied by the Barnes Engineering Company, Stamford, Connecticut (Reference 17).

It will be observed that the experimental values of the relative spectral response of the solar channel has a maximum value of unity at 1.5 microns. Moreover, the relative response is 90% or greater

Table 2
RELATIVE SPECTRAL RESPONSE OF TIROS RADIOMETER 303

Wavelength	Relative Spectral Response		Wavelength	Relative Spectral Response	
Microns	Exper.	Calc.	Microns	Exper.	Calc.
.30	.357	.317	2.0	.922	.968
.32	.458		2.1	.922	
.35	.552		2.2	.922	.912
.37	.570		2.3	.933	
.40	.623	.525	2.4	.966	.870
.45	.664		2.5	.911	
.50	.692	.574	2.6	.863	.861
.55	.712		2.7	.896	
.60	.720	.672	2.8	.929	.861
.65	.737		2.9	.918	
.70	.737	.779	3.0	.915	.859
.75	.804		3.1	.896	
.80	.725	.740	3.2	.900	.840
.85	.712		3.3	.900	
.90	.890	.844	3.4	.849	.824
1.0	.927	.939	3.5	.728	
1.1	.957		3.6	.607	.710
1.2	.974	.981	3.7	.523	
1.3	.991		3.8	.501	.546
1.4	.983	.992	3.9	.435	
1.5	1.00		4.0	.339	.494
1.6	.991	1.00	4.1	.317	
1.7	.978		4.2	.134	.298
1.8	.944	.981	4.3	.075	
1.9	.922		4.4	.073	.066
			4.5	.069	
			4.6	.035	.011

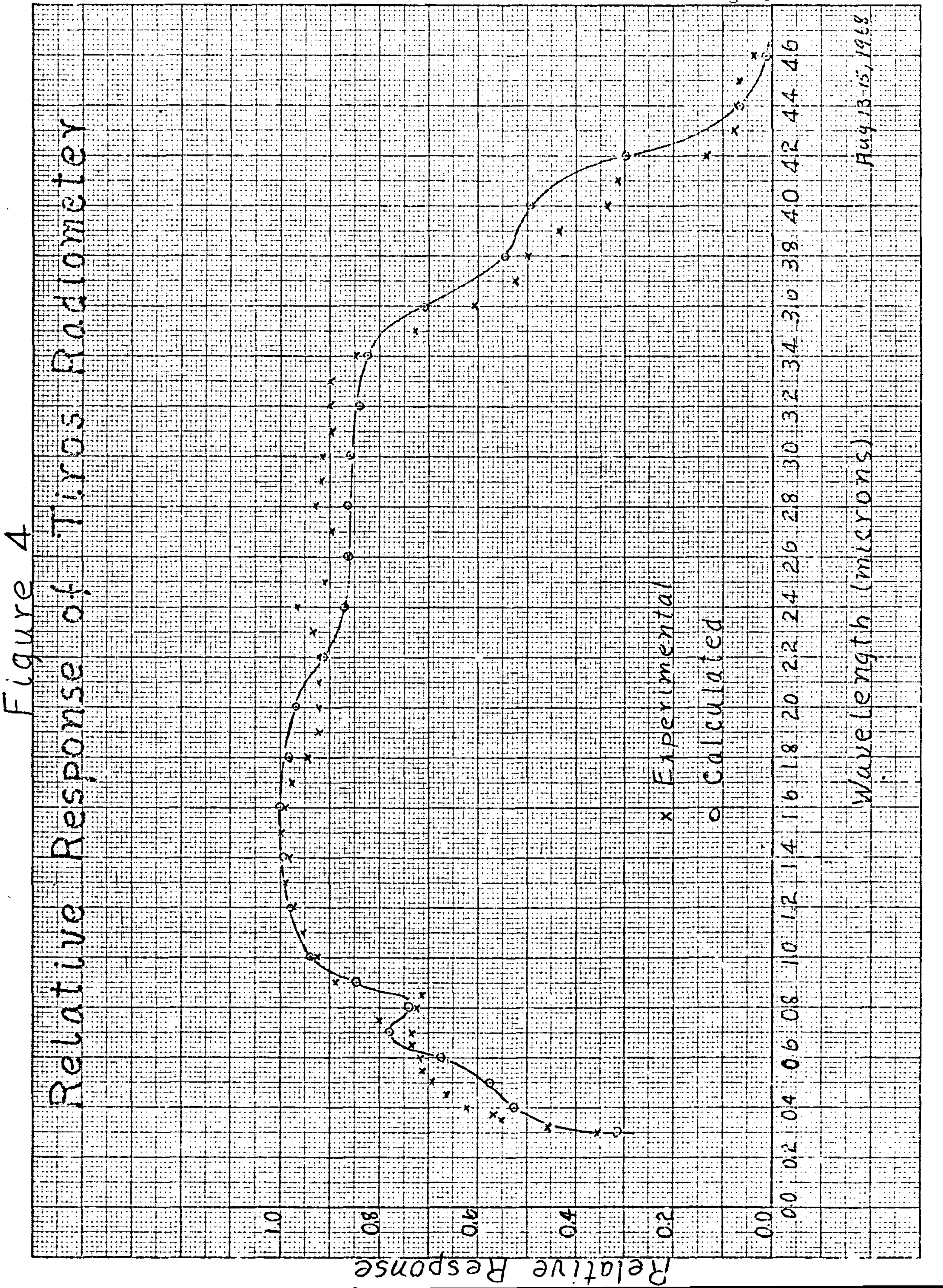

Figure 4

Relative Response of Tiros Radiometer

in the range 0.9 micron to 3.3 microns, and drops fairly rapidly below 0.9 micron and above 3.3 microns. In the range 0.9 micron to 1.6 microns the experimental values agree reasonably well with the theoretical calculations, with a difference of one percent or less. In the range 1.6 microns to 3.3 microns the differences are approximately five percent. From 3.3 microns to 4.7 microns the experimental values decrease more rapidly than do the theoretical values.

EVALUATION OF THE PERMANENT SET-UP

After the permanent set-up had been completed, the radiometer #303 which was used in the preliminary tests, was no longer available for the final check-out of the system. Hence unmounted thermistor bolometers manufactured by Barnes Engineering were chosen for the evaluation, since they are the same type of bolometer as those used in the radiometer #303. In the case of these unmounted bolometers, however, the relative spectral response is due solely to the spectral response of the thermistor flake, completely unmodified by any lenses, filters or mirrors.

In order to shield the bolometer from stray light and other types of radiation; it was mounted inside an aluminum box 3.75 x 6x8 inches and grounded to the system. This positioned the thermistor flake 3/8 inch from a 0.25 inch diameter hole through which the flake received radiation from the beam splitter.

The experimental procedure used was the same as that outlined above for the preliminary set-up. In making the measurements necessary to obtain the spectral response several problems were encountered. (a) The back side of the chopper blades provides room temperature blackbody radiation which is 180° out of phase with the incident radiation which the chopper converts into a 13 Hz signal. The intensity of this out-of-phase radiation was greatly reduced by limiting the size of the exit slits on the beam splitter. The remainder of this out-of-phase signal was eliminated by proper adjustment of the narrow bandpass A.C. amplifier and voltmeter. (b) It was found that the alignment of the beam splitter with the radiation coming from the monochromator is very critical and must be made with extreme care. The entrance and exit beams must be carefully centered in the entrance and exit slits respectively. In addition, it was found that improper orientation and incorrect distance of the detector from the exit slit of the beam splitter may give an unsymmetrical 13 Hz waveform. Hence the simplest way to obtain good alignment is to make use of a good oscilloscope to observe the amplitude and shape of the signal wave form while the adjustments are being made. (c) In order to determine the relative spectral response of a detector, it must be compared with a detector having constant spectral response of relatively high efficiency. It has been shown (reference 18) that the nearest approach to a perfect detector is a black radiation detector constructed in the form of a cone of small angle and coated with carbon or other black on the inside surface. While this is the type of detector which is planned for the permanent set-up, unfortunately it was not available for the tests although it had been on order for months. Hence Reeder thermocouples with either quartz or cesium iodide windows were used. Eisenman (et al) have shown (reference 18) that the response of such thermocouples decreases almost linearly with increasing wavelength from 1 micron to 14 microns. For this reason the measured response of the bolometer was corrected for the transmissivity of the thermocouple windows and also for the decreasing response of the thermocouple with increasing wavelength. (d) A fourth and as yet unresolved problem was observed in the ultraviolet and in the infrared portions of the range examined, especially in the regions where the spectral radiance of the source is rather low. The dual beam chopper (beam splitter) is designed to be driven by an 1800 rpm synchronous motor by means of "No-Slip" geared pulleys and a common "No-Slip" positive drive belt. The gear ratio is such that the chopper sends a 13 1/8 Hz output signal to both the reference detector and the detector being studied. Since the internal oscillator of the lock-in amplifier and voltmeter is designed to operate at 13 Hz, the interaction of the two signals gives a beat frequency of 1/8 Hz. While this is not too significant in the case of a strong signal, it becomes practically impossible to compare the two detectors when the signals are weak. This means that the present system will not be practical unless/until the frequency of the chopper and of the oscillator of the lock-in voltmeter can be made the same.

The response of the thermistor bolometer was measured over the range 0.45 micron to 5.8 microns, and normalized to unity at the wavelength of maximum response. Table 3 gives the data obtained for the thermistor bolometer #2875.

Table 3
RELATIVE SPECTRAL RESPONSE OF
THERMISTOR BOLOMETER # BE2875

Wavelength (microns)	Relative Spectral Response	Wavelength (microns)	Relative Spectral Response
.45	.264	2.5	.913
.50	.397	2.6	.915
.55	.477	2.7	.911
.60	.578	2.8	.910
.65	.714	2.9	.897
.70	.757	3.0	.923
.75	.826	3.2	.930
.80	.861	3.4	.905
.85	.951	3.6	.891
.90	.995	3.8	.872
1.0	.998	4.0	.889
1.1	1.000	4.2	.850
1.2	.979	4.4	.853
1.3	.979	4.6	.848
1.4	.967	4.8	.887
1.5	.966	5.0	.878
1.6	.960	5.2	.822
1.7	.957	5.4	.911
1.8	.947	5.6	.975
1.9	.945	5.8	
2.0	.941		
2.1	.933		
2.2	.932		
2.3	.929		
2.4	.924		

Since obtaining the foregoing results, the experimental set-up has been modified as follows: The oscillator frequency cards of both narrow bandpass A. C. amplifiers and voltmeters were replaced by frequency programmers. With these programmers it is possible to select oscillator frequencies from 1 Hz to 999 Hz. This made it possible to select an oscillator frequency of 13.1 Hz which is very close to the fixed frequency (13.125 Hz) of the dual beam splitter. This largely overcomes the problem discussed under d, page 19, and allows a comparison of two detectors for weaker signals than was possible previously.

CONCLUSIONS

An examination of the experimental results leads to the following observations:

(a) The permanent set-up is a very convenient arrangement to measure the relative spectral response of a detector by obtaining the record of the ratio of two detectors by means of a chart recorder.

(b) The frequency programmer has made it easier to measure weak signals. However, it would be possible to detect even weaker signals if it were possible to obtain exact synchronization between the oscillator frequency (13.1 Hz) and the frequency of the dual beam chopper frequency (13.125 Hz).

(c) It would seem that all sources of stray light have not been eliminated. It may prove necessary to install additional baffles in the reimaging optics to try to cut down on the amount of stray radiation.

ACKNOWLEDGMENTS

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PHYSICS DEPARTMENT, COLUMBIA UNION COLLEGE

FINANCIAL REPORT

GRANT NGR 21-023-001 (January to August, 1968)

Use of Grant Funds	Proposed	Actual
Salaries	$4,200.00	$4,200.00
Overhead	630.00	630.00
Equipment & Supplies	1,170.00	1,100.02
Totals	$6,000.00	$5,930.02

Cost Sharing	Proposed	Actual
Salaries		$700.00
Equipment Purchased by Dept.	$444.90	447.80
Totals	$444.90	$1,147.80

GRANT NGR 21-023-001, SUPPLEMENT NO. 1 (January to June, 1969)

Use of Funds	Proposed	Actual
Salaries	$3,600.00	$3,600.00
Overhead	540.00	540.00
Equipment & Supplies	360.00	415.63
Totals	$4,500.00	$4,555.63

Cost Sharing	Proposed	Actual
Salaries		$768.75
Equipment Purchased by Dept.	$225.00	239.00
Totals	$225.00	$1,007.75

SUMMARY OF EXPENDITURES (Original Grant and Supplement)

Total Funds Received	$10,500.00	
Total Funds Disbursed	$10,485.65	
Salaries and Equipment not Paid by Grant Funds		$2,155.55

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