On the Applicability of Silicon Cells in Atmospheric Radiation Studies

by
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Technical Paper No. 113
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1. INTRODUCTION

Silicon cells, primarily fabricated to be used as "solar batteries" with high voltage output are increasingly employed as detectors for atmospheric radiation measurements. These sensors show many advantages compared with conventional radiation sensors. For example, their ruggedness makes them useful on fast moving and vibrating vehicles, such as cars or aircraft, and their low cost enables the scientist to use numerous instruments for extensive studies of local radiation differences.

However, the spectral response of silicon cells differs considerably from generally used atmospheric radiation instruments such as pyrheliometers, pyranometers, and albedometers. These instruments, usually employed for the determination of the short wave radiation flux, are thermal receivers consisting of a black (or black and white) painted surface. The temperature of the receiver, when exposed to atmospheric radiation is measured by means of thermoelectric or bolometric devices. The black or the black and white receiver permits an almost "flat" spectral response to radiation within the range of the solar radiation. Thus, determinations of the amount of radiative energy can be made.

Silicon cells show a pronounced spectral response according to the photovoltaic process of the particular semi-conductor. This response not only covers just part of the solar spectrum but also weighs the incoming radiative energy according to its wave length. An immediate conversion of the readings from silicon cells to those of pyranometers as such is not recommended. But if a conversion method has been worked out previously for the various atmospheric conditions and objects in question a reduction to energy values is acceptable. Only if these developed relations prove to be constant for changing atmospheric and environmental conditions, then even sensors with strong spectral response can be used for atmospheric radiation studies.

Selcuk and Yellot (1962) and Yellot, Chamness, and Selcuk (1962) studied the response of silicon cells when exposed to solar and sky (global) radiation and compared the results with measurements received with pyranometers and pyrheliometers. Taking into account the limitations of silicon cells, such as non-linearity between radiative flux and photocurrent and temperature effects, they found good agreement between the output of pyranometers and silicon cells for global-radiation. This result is not surprising since the spectral distribution of the global-radiation on a horizontal surface shows almost no change with solar elevation (or time of the day), as pointed out by Moeller (1957). For direct solar radiation, however, the authors found less agreement. By applying some corrections, they could compensate for the effect of solar elevation and the influence of air mass, both of which are responsible for changes in the spectral distribution of the solar radiation. However, one must recognize that this effect is dependent on atmospheric turbidity and therefore varies with the location, the time of day, the season, weather condition, etc. The authors, therefore, did not recommend the use of silicon cells for the general detection of direct solar radiation. The same consideration holds for diffuse sky radiation, which has a spectral distribution considerably different from global radiation, because its maximum is shifted to the blue, where the sensitivity of the silicon cell decreases rapidly.

So far, silicon cells have not been tested for their applicability to reflection measurements under natural conditions. Considering the good agreement of this instrument with conventional pyranometers for global radiation, the reflectivity of surfaces measured with an inverted instrument under natural conditions (albedo) should provide comparable results as long as materials of no pronounced spectral reflectivity are under consideration. Unfortunately, only stones, sand, and water show a more or less uniform reflectivity. Vegetation, snow fields, and clouds exhibit a distinct spectral response, which , together with the spectral response of the silicon cell, could considerably influence the albedo values gathered with these instruments. As silicon cells recently were used particularly for albedo measurements from aircraft, the present study shall show the possibilities and limitations of such an instrument. As a first approach, albedo measurements were taken at ground level for the most general natural materials.

2. INSTRUMENTS AND METHODS

For the albedo comparisons in this study an Eppley pyranometer and a so-called Sol-A-Meter from the Yellott Solar Energy Laboratory were used (Fig. 1). This silicon cell is already prepared for atmospheric radiation measurements, as described later.

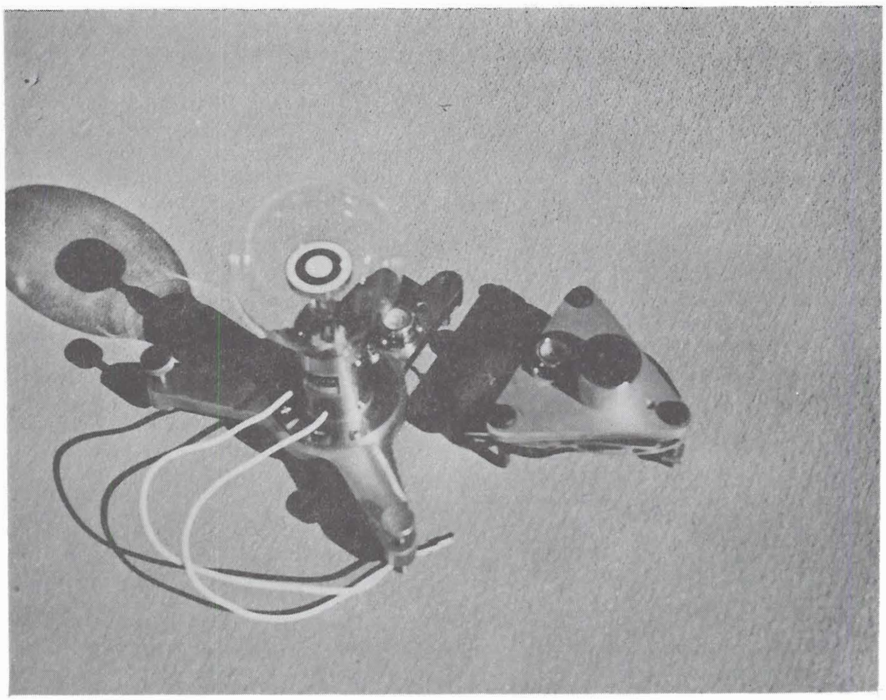

Fig. 1
Eppley - pyranometer and Sol-A-Meter used in this study.

To compare the results of albedo measurements from the two instruments and to study the influence of the spectral response of silicon cells on albedo, some physical properties must first be checked. These are:

a) linear response
b) temperature effect
c) cosine effect

a) The thermoelectrical device of the pyranometer should give a linear radiation versus current characteristic. This was shown, for example, in a study of two similar pyranometer types, namely, one Solarimeter and two Star Pyranometers (Dirmhirn, 1958). A rotating sector was used to vary the direct incoming solar radiation in increments of 22.5°. Linearity has been found for all three instruments within one percent.

Silicon cells, as well as selenium cells, show linearity of the photocurrent versus illumination only for the short-circuit. The higher the external resistance, the more the linearity degrades. Fig. 2, taken from Goerlich (1951), shows the deviation of the photocurrent of selenium cells from proportionality for several ranges of external resistance. In the Sol-A-Meter device, a low resistor (a few tenths of an ohm) shunts the photocurrent, which then can be measured with any recording potentiometer. In this case, the photocurrent to radiative intensity characteristic is linear.

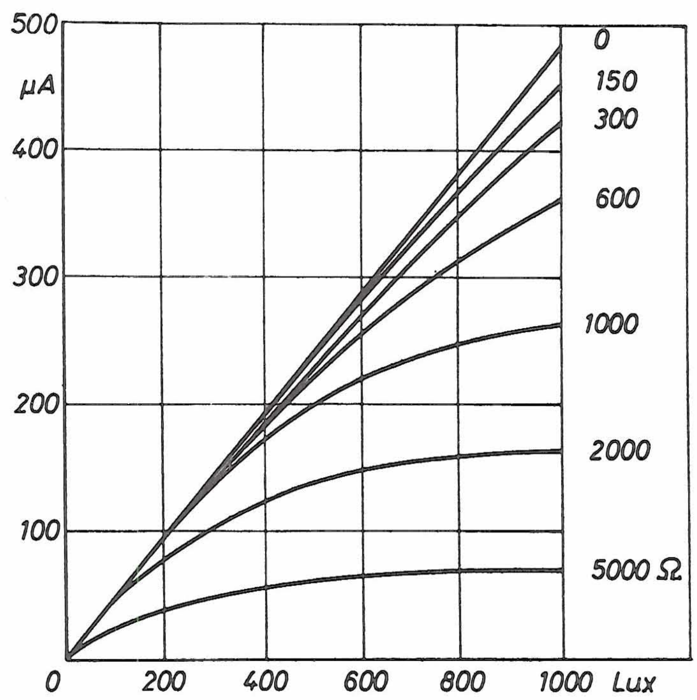

Fig. 2
Conversion curves relating photo current to illumination at different external resistance for selenium cells.

b) A temperature effect of 3.5% (average for 5 tested pyranometers) within 60° F. (from 40 to 100° F.) has been found by MacDonald (1951), resulting in a temperature coefficient of 0.058% per degree F.

The temperature effect of the silicon cell is highly reduced in the short-circuit current as shown in the data sheets of Solar System, Inc. In the Sol-A-Meter device, by using a bead thermistor with negative temperature coefficient to shunt the photo-current, the temperature effect has been shown (Yellot, Chamness and Selcuk) to be about 10% for a temperature range of 100° F. (Fig. 3).

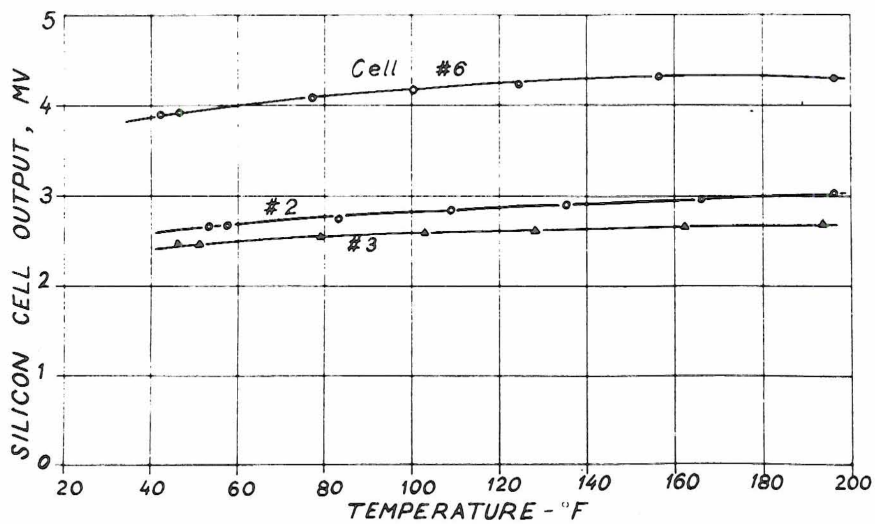

Fig. 3

Variation of short-circuit current for typical silicon cells under constant tungsten illumination over the temperature range 40 to 195 degrees F.

In relative measurements carried out in albedo determination, the temperature effect does not influence the results, because it applies to the reflected as well as to the incoming radiation, taken at the same time and with the same instrumental conditions.

c) Every radiation instrument with a horizontal (2π, 180° opening angle) receiver surface demonstrates a deviation from the expected cosine response. Most of the pyranometers, however, provide an output according to the cosine law, $I = I_o \cos \beta$ (where I_o is the radiation at $\beta = 0°$ angle of incidence) up to angles of about 60°. Deviations increase rapidly with increasing angles of incidence.

Investigations on Eppley pyranometers, with respect to the cosine response, were carried out by Woertz and Hand (1941), MacDonald (1951), and Fuquay and Buettner (1957). Figure 4 shows the results found by MacDonald (4a), including the data given

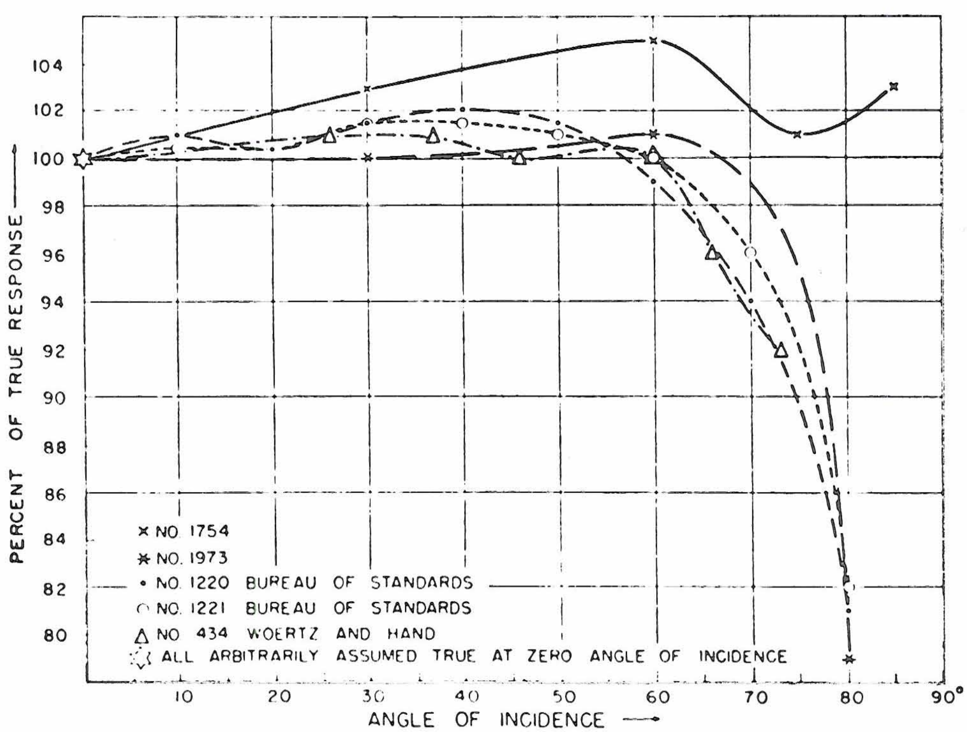

Fig. 4a
Percent of true response as a function of angle of incidence for a number of pyrheliometers.

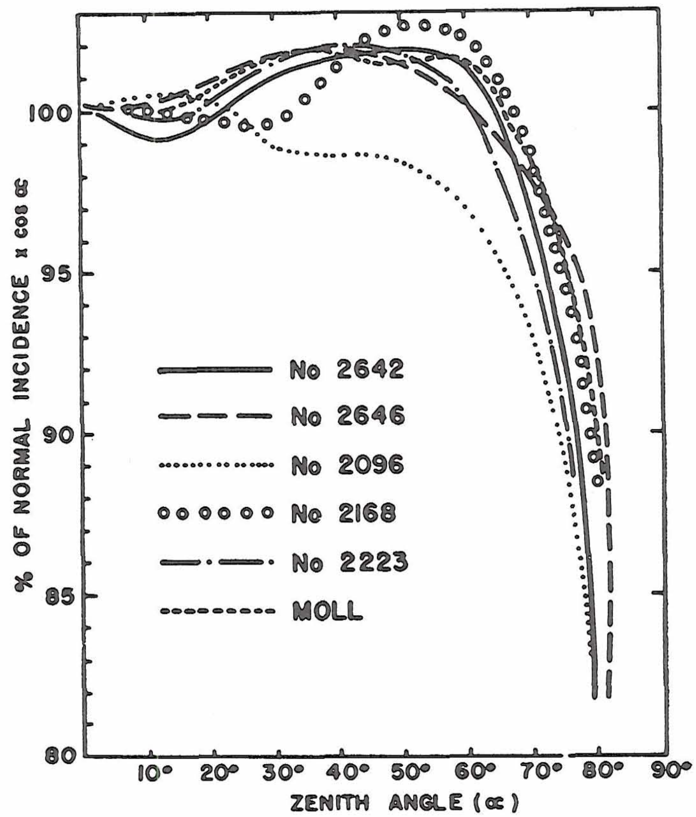

Fig. 4b
Deviation of five Eppley pyranometers and one Moll-Gorczynski pyranometer from the cosine law for different zenity angles.

by Woertz and Hand, and those published by Fuquay and Buettner (4b). The deviations at incident angles 60° are due to some specular reflection of the black and white paint and are hard to avoid. They have been improved somewhat with the introduction of new paints, but measurements with pyranometers at solar elevations of more than about 65° are still doubtful.

The deviation from the cosine response for silicon cells, as found by Selcuk and Yellott is shown in Fig. 5a. According to this figure, the incorrect cosine response is significant and must be considered in any measurements. Other results for particular instruments showed much better agreement (Fig. 5b). To check the curve in Fig. 5, a pyranometer and a Sol-A-Meter were plugged

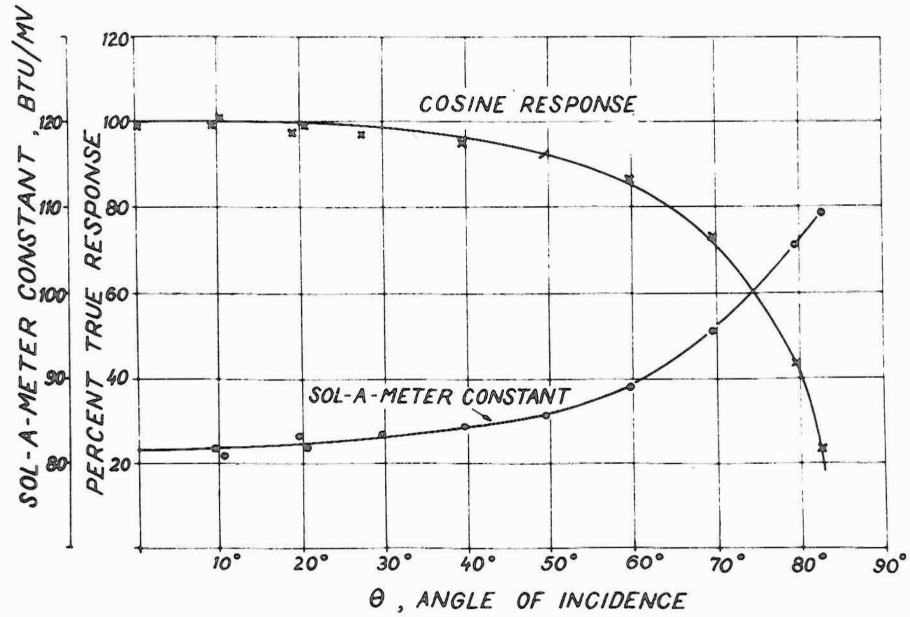

Fig. 5a
Variation of cosine response for silicon cells at incident angles from 0 to 90 degrees.

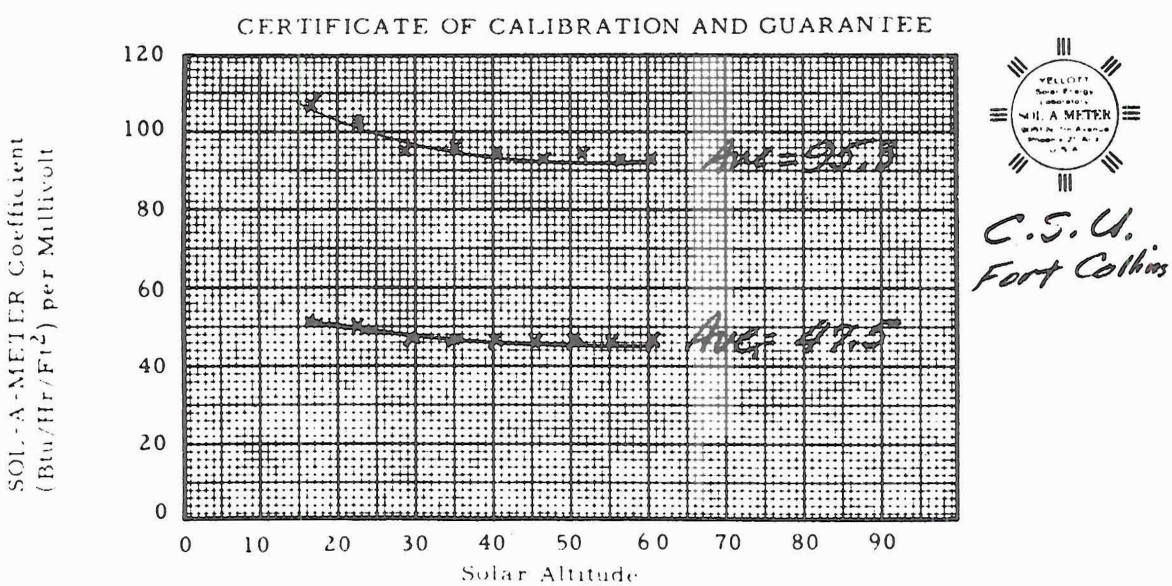

Fig. 5b
Cosine response of particular silicon cells, taken from Calibration certificates.

into the x and y components respectively of an X-Y plotter. The instruments were mounted horizontally on the roof of the Colorado State University Engineering Building, Fort Collins, Colorado. During May 29, 1966, a perfectly clear day, the output of the two instruments was recorded. The range on the x and y scale was adjusted so that at the highest solar elevation both instruments would show the same voltage. A 45° line then exhibits the same cosine response for both instruments. Records were taken from sunrise until after noon (5:40 a.m. to 12:40 p.m.) at intervals of 10 minutes. In the course of the measurements the instruments were turned around their vertical axis to detect any possible azimuth effect.

With the Sol-A-Meter used, a considerable azimuth effect could be seen. When the electrode bar was directed toward the sun, deviation was twice as much as when the bar was on the side opposite to the sun. Therefore, the instrument was used only in one position for all further comparisons.

The differences of the readings between the two instruments have been plotted in Fig. 6a. Applying the average deviation of Eppley pyranometers from the cosine law (Fig. 4) the measurements give a much less pronounced deviation from the cosine law for the Sol-A-Meter than those shown in Fig. 5. In Fig. 6b, the circles show the difference between the two instruments in the deviation from the cosine law (average pyranometer deviation applied), and the solid line is taken from Fig. 5. Our results show a better agreement, especially for lower angles of incidence. The deviation starts here only about 60° (30° solar altitude), which seems to be acceptable for our particular study. The deviation of silicon cells from the cosine law under natural conditions is partly reduced by the scattered radiation of the sky.

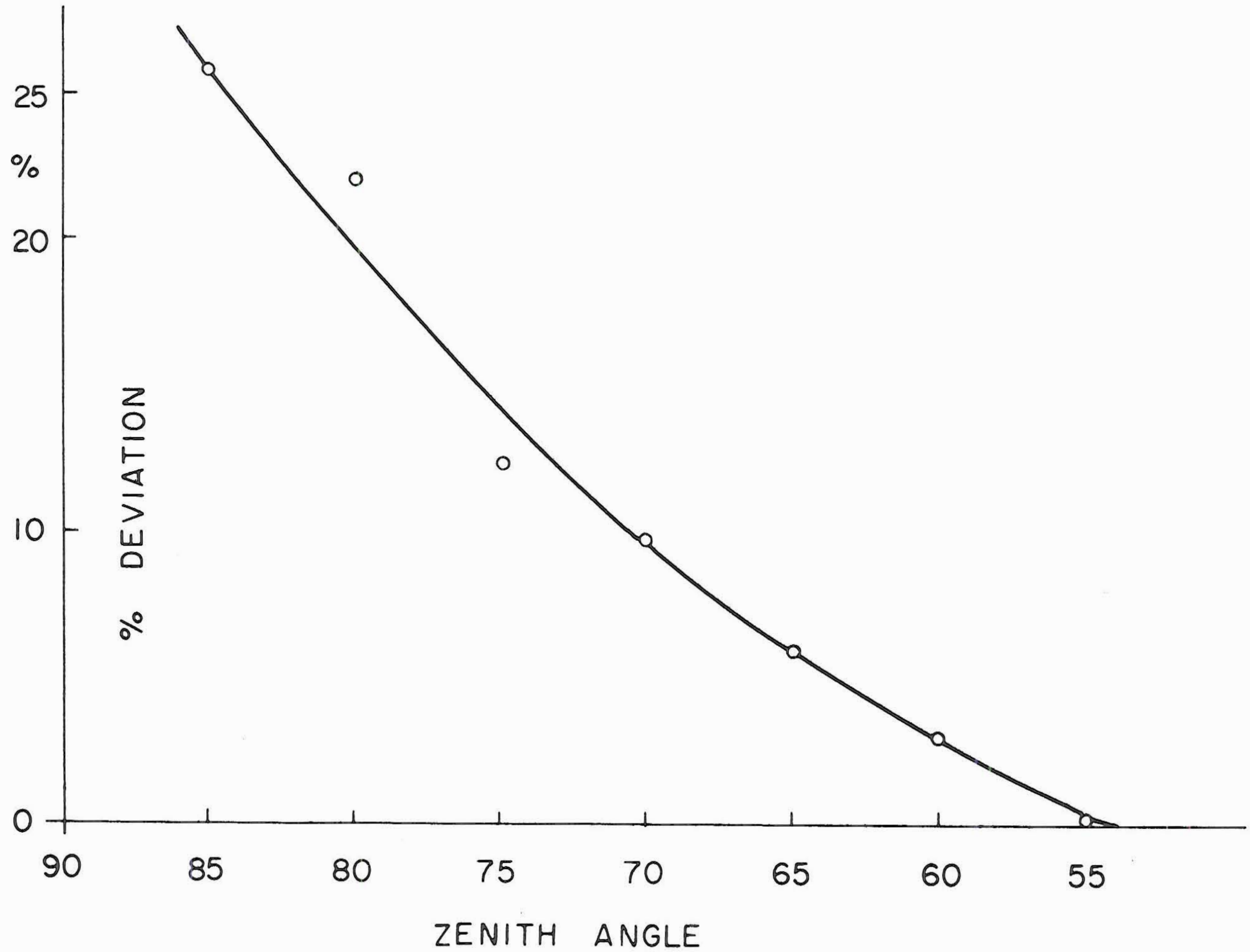

Fig. 6a
Deviation of the reading of the Sol-A-Meter from those of the pyranometer in a comparison on an X-Y-Recorder at Colorado State University

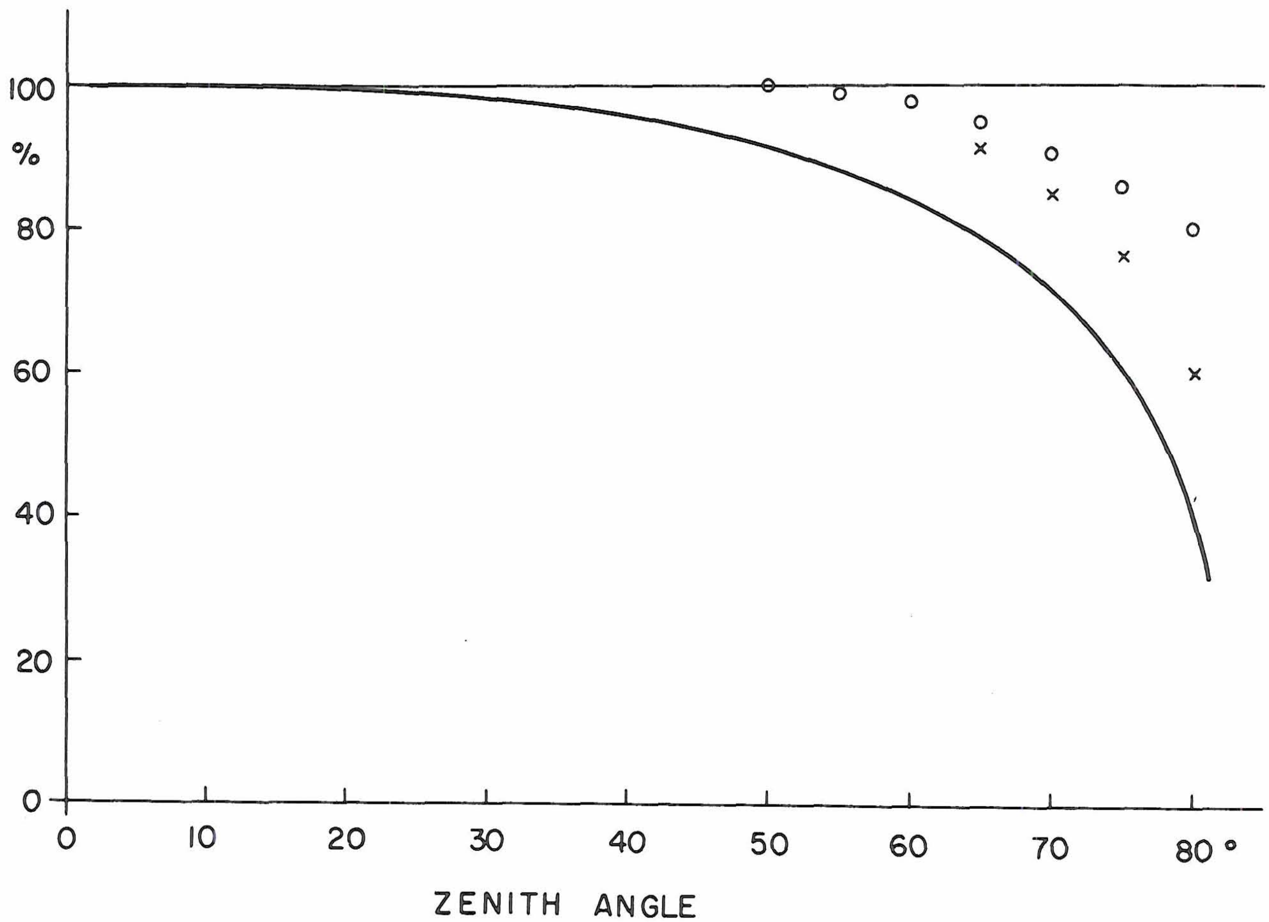

Fig. 6b
Deviation of the reading of the Sol-A-Meter from the cosine law. Circles = taken from Fig. 6a, crosses = same values, but average deviation of pyranometers from Fig. 4 applied, solid line = cosine response given by Selcuk and Yellott in Fig. 5a.

Since field measurements of albedo are generally accurate within a few percent, all the previous mentioned sources of error will not influence comparisons considerably, especially if low sun angles are avoided.

The albedo measurements were carried out on the ground because more stable conditions could be expected there than with mountings on the aircraft. Tests taken from aircrafts shall follow.

A series of measurements is comprised of 5 single measurements, each recording incoming, reflected, and again incoming radiation to take care of possible changes of the incoming radiative flux during the course of the measurement. The albedo was calculated for every single measurement taking

$$a = \frac{I_r}{I_1 + I_2} \cdot 100$$

a = albedo
I_1, I_2 = incoming solar and sky radiation
I_r = reflected radiation

For the measurement of the incoming radiation, the instrument was placed parallel to the surface under consideration: for the recording of the reflected radiation the instrument was held inverted above the surface at a distance of about 1/2 meter (see Fig. 7). Investigations of the influence of the shadow of the instrument on the reading at different distances from the surfaces have shown that no error should be expected if the particular instrument (according to its size) is held at a distance of at least 30 cm at solar zenith angles greater than 40°.

Sloping terrain has been avoided as far as possible. If it was necessary to include measurements above slopes, the instrument was held parallel to the slope for the incoming as well as for the

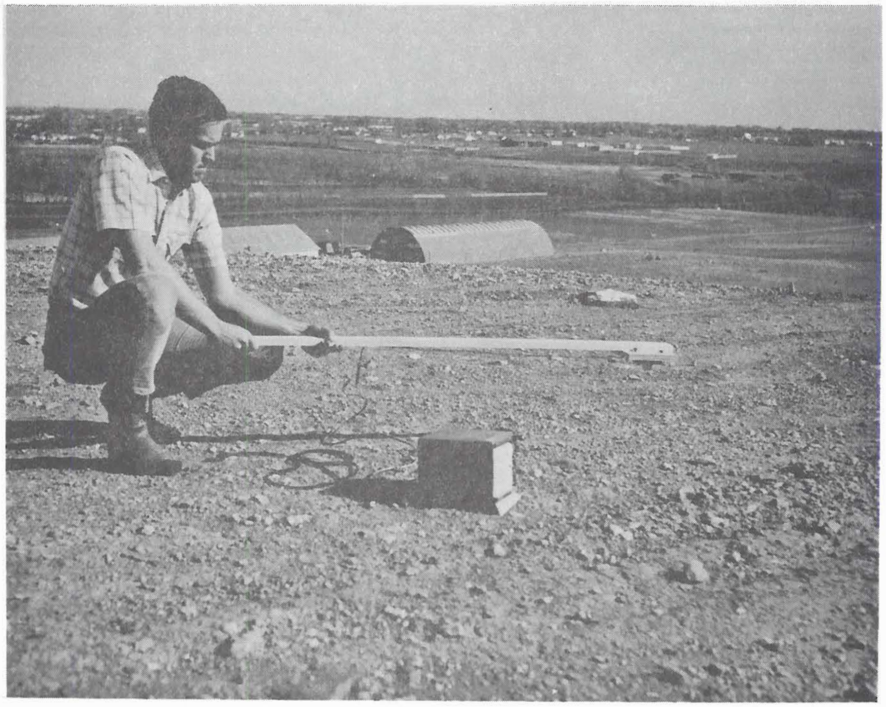

Fig. 7
Albedo measurement at Colorado State University

reflected radiation. Figure 8 explains the difference in the results gained with this method and those with so-called "albedometers", which are used in horizontal mounting. Assuming an isotropic reflection pattern, a slope of 30° at 60° solar altitude will receive normal incident solar radiation, I. The reflected radiation is a · I, "a" being the integrated reflectivity over all wave lengths of the incoming radiation, i. e. the albedo. Using an albedometer with

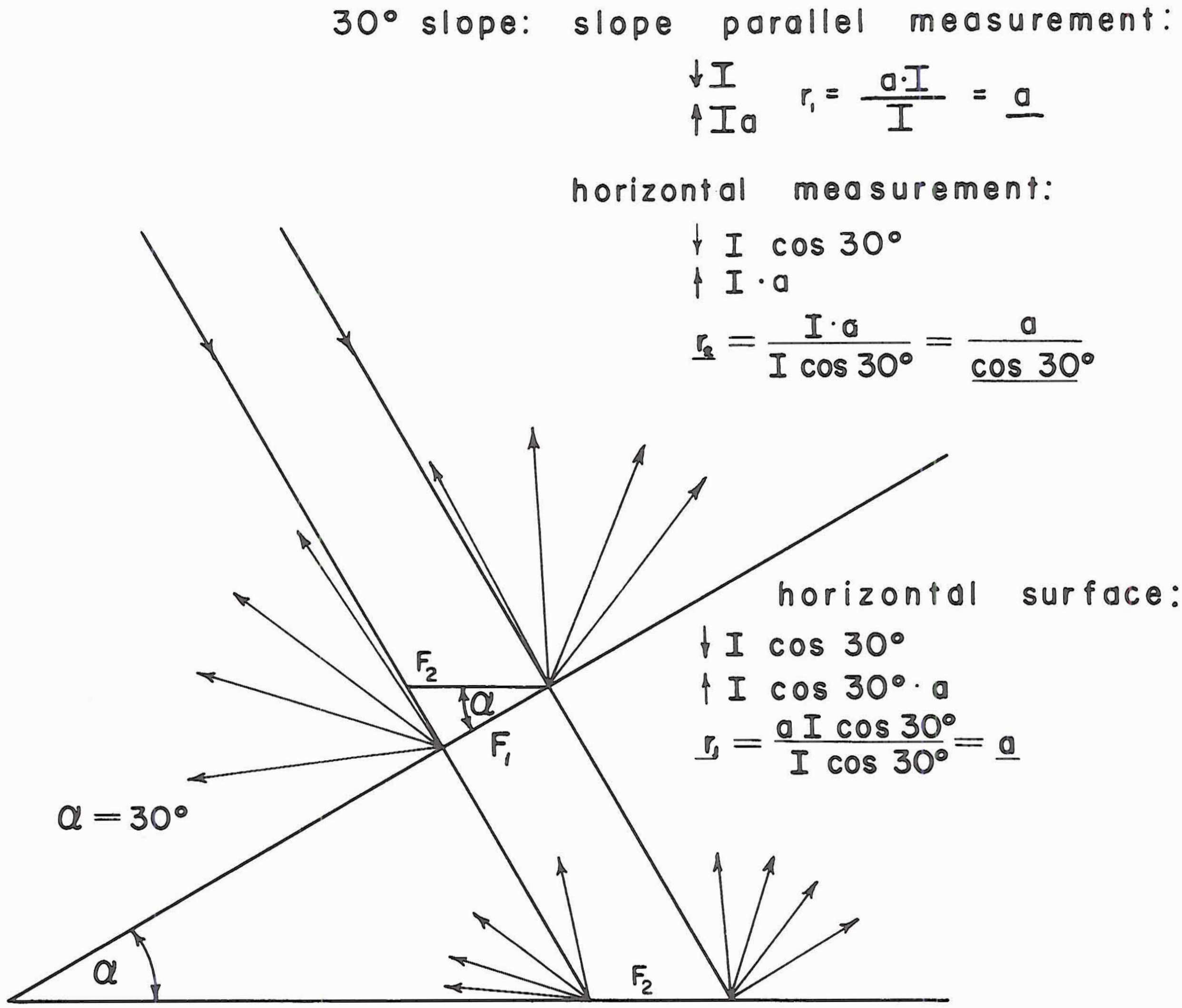

Fig. 8

Geometry of slope-parallel measurements and readings with so-called "albedometers" (horizontal mounting), assuming isotropic reflection. Determinations of albedo from a surface of entirely the same reflectivity but under different slope angle show the same result only if the measurements are performed parallel to the slope.

horizontal mounting, the detected incoming radiation would be $I \cdot \cos \alpha$, while the reflected radiation, assuming isotropy, still would be $a \cdot I$. Calculation of albedo would give

$$r_1 = \frac{a \cdot I}{I} = a \quad \text{in the slope-parallel case,}$$

$$r_2 = \frac{a \cdot I}{I \cdot \cos \alpha} = \frac{a}{\cos \alpha} \quad \text{in the horizontal measured case.}$$

As the geometry of the two instruments, the pyranometer as well as the silicon cell, is the same, namely 180° or 2π opening angle, no error is possible in comparing the instruments from this point of view. Nor can the different response time of the two instruments cause any error, if readings are taken only during stable weather conditions so that each of the instruments can reach equilibrium.

3. RESULTS OF COMPARISONS

The comparative measurements were taken between June, 1966, and February, 1967. Stable weather conditions were chosen - either cloudless or completely cloud covered sky. During days without clouds, measurements were carried out in the sunshine as well as in the shadow for surfaces with pronounced spectral response.

Table 1 contains all available results. A comparison of the measured albedo values for water, soil, concrete, and green plants is shown in Fig. 9. Within an acceptable variance, the points lay around the 45° -line. Only the reflection of green plants is slightly too high as measured by the Sol-A-Meter.

TABLE I

All measured Albedo - Values

Day & Time	Solar Altitude	Instrument	Output		Albedo %	Surface	Radiation Clear Sky		
			Incoming	Reflected			Solar + Sky	Sky (Shadows)	Covered Sky
7/12/66 - 9:45	65.2°	P	38.5	8.8	22.9%	Grass	+		
7/12/66 - 10:00	67.4°	S	45.9	11.3	24.7%	Grass	+		
7/12/66 - 10:00	67.4°	P	38.6	8.8	22.9%	Grass	+		
8/15/66 - 15:30	30.3°	S	41.8	2.5	5.9%	Water	+		
8/15/66 - 15:35	29.4°	P	33.9	2.2	6.6%	Water	+		
8/15/66 - 15:40	28.5°	P	38.2	10.8	28.3%	Concrete	+		
8/15/66 - 15:45	27.2°	S	48.9	14.0	28.5%	Concrete	+		
8/15/66 - 16:06	22.7°	P	35.4	9.0	25.6%	Red Soil	+		
8/15/66 - 16:15	21°	S	24.1	7.0	29.2%	Red Soil	+		
8/15/66 - 16:27	18.8°	S	21.2	7.1	35.2%	Grass	+		
8/15/66 - 16:27	18.8°	P	23.6	8.0	33.7%	Grass	+		
8/17/66 - 10:12	61.8°	P	39.2	8.4	21.4%	Red Soil	+		
8/17/66 - 10:20	62.8°	S	32.8	7.2	21.1%	Red Soil	+		
8/17/66 - 10:45	64.7°	P	40.5	10.0	24.7%	Grass	+		
8/17/66 - 11:00	66°	S	35.2	10.3	29.35%	Grass	+		
8/17/66 - 12:50	60.3°	S	35.0	1.7	4.9%	Water			+
8/20/66 - 4:04	23.2°	S	30.0	4.0	13.2%	Water	+		
8/20/66 - 4:10	21.8°	P	29.3	3.9	13.1%	Water	+		
8/20/66 - 5:02	11.6°	S	13.3	2.5	18.5%	Water	+		
8/20/66 - 5:06	10.8°	P	13.6	2.8	20.7%	Water	+		
8/20/66 - 10:30	63.5°	P	39.4	2.5	6.5%	Water	+		
8/20/66 - 11:45	66.3°	P	40.7	1.95	4.8%	Water	+		
8/20/66 - 12:00	65.2°	S	35.3	1.45	4.1%	Water	+		
8/20/66 - 12:20	63.3°	P	40.2	2.0	4.9%	Water	+		
8/20/66 - 12:28	62.7°	S	46.2	2.2	4.8%	Water	+		
8/20/66 - 12:28	62.8°	S	21.4	2.0	9.3%	Water			+
8/22/66 - 9:33	57°	P	37	22.5	61.5%	Snow	+		
8/22/66 - 9:33	57°	P	11.0	7.2	65.5%	Snow		+	
8/22/66 - 9:40	57.8°	S	11.6	8.6	70.2%	Snow	+		

TABLE I
(Continued)

Day & Time	Solar Altitude	Instrument	Output		Albedo %	Surface	Radiation Clear Sky		
			Incoming	Reflected			Solar + Sky	Sky (Shadows)	Covered Sky
8/22/66 - 9:40	57.8°	S	12.5	7.8	63.5%	Snow		+	
8/22/66 - 12:31	62.4°	P	18.0	1.8	9.9%	Water			+
8/22/66 - 12:47	60.5°	S	32.6	2.6	7.8%	Water			+
8/22/66 - 12:55	59.9°	P	28.6	2.0	7.2%	Water			+
8/22/66 - 13:15	57.5°	P	26.0	5.2	19.37%	Red Soil			+
8/22/66 - 13:27	55.8°	S	28.7	5.9	20.4%	Red Soil			+
8/22/66 - 13:42	53.8°	S	24.0	4.7	19.4%	Red Soil			+
8/22/66 - 13:44	52.5°	S	16.0	3.0	18.6%	Red Soil			+
8/22/66 - 14:10	48°	S	23.2	6.8	29.6%	Concrete			+
8/22/66 - 14:13	47.4°	P	16.8	4.2	25.3%	Concrete			+
8/22/66 - 14:27	44.7°	P	13.35	3.4	25.8%	Concrete			+
8/22/66 - 14:31	44°	S	15.5	4.7	30.4%	Concrete			+
12/14/66- 10:00	20.3°	P			35.0%	Concrete			+
12/14/66- 10:15	21.5°	S			35.3%	Concrete			+
12/14/66- 13:00	24.7°	P			36.9%	Concrete			+
12/14/66- 13:15	23.8°	S			37.1%	Concrete			+
12/15/66- 10:00	20.3°	S			8.60%	Gravel	+		
12/15/66- 10:15	21.5°	P			10.59%	Gravel	+		
12/28/66- 10:30	22.8°	S			70.3%	Snow	+		
12/28/66- 10:45	23.8°	P			63.5%	Snow	+		
1/17/67 - 10:46	25.4°	S	51.8	46.5	90.7%	Snow	+		
1/17/67 - 10:55	26.4°	P	53.7	43.0	80.3%	Snow	+		
1/17/67 - 11:20	27.1°	P	63.8	51.0	79.8%	Snow	+		
1/17/67 - 12:00	28.2°	P	88.3	76.4	86.9%	Snow		+	
1/17/67 - 12:15	27.8°	P	67.5	54.0	79.6%	Snow	+		
1/17/67 - 12:30	27.4°	S	57.5	51.0	88.0%	Snow	+		
1/17/67 - 12:45	27.0°	S	32.75	28.75	88.0%	Snow	+		

P= PYRANOMETER
S= SOL-A-METER

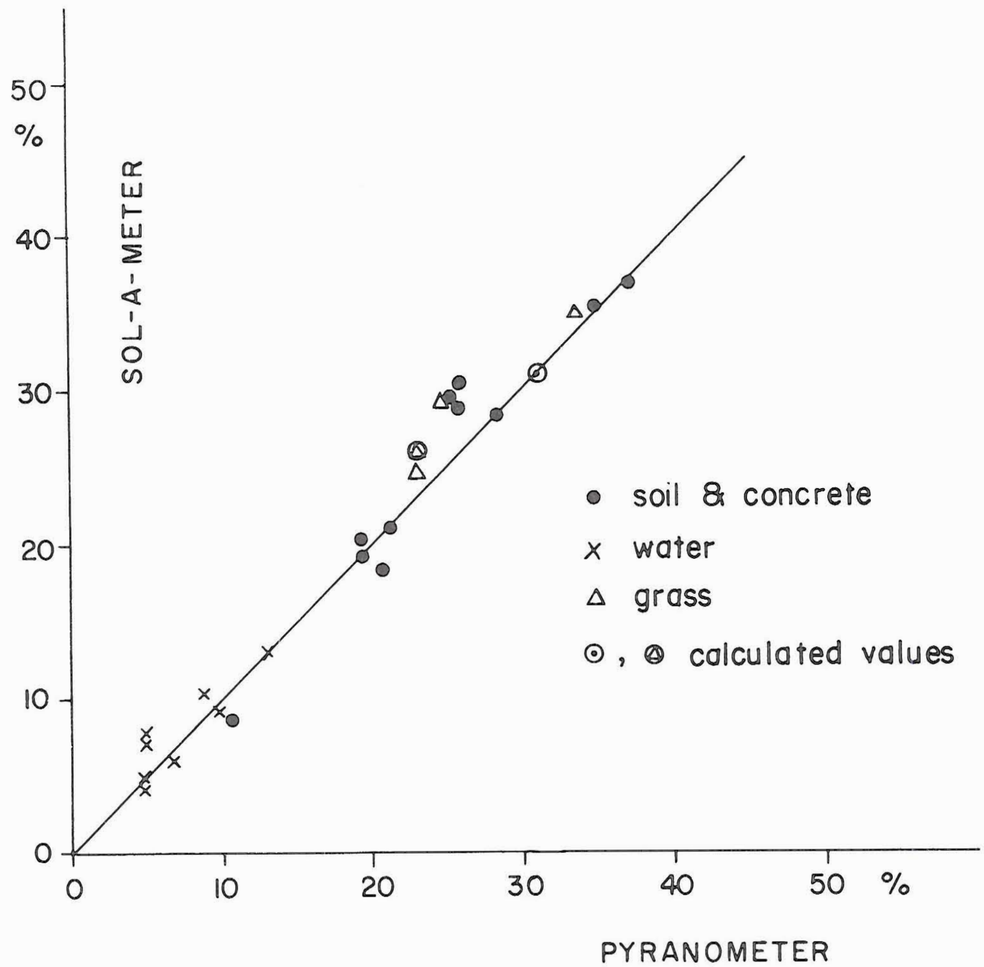

Fig. 9
Comparison of albedo-measurements with pyranometer and Sol-A-Meter for some natural surface materials. Circles are calculated values (see part IV).

The measured values for snow are plotted in Fig. 10. While the albedo values in the shadow are nearly the same for both instruments; the values obtained in sunshine with the Sol-A-Meter considerably exceed those from the pyranometer. The same pronounced differences have been found from comparisons of pyranometers with selenium cells for a more comprehensive material (dashed line). The "calculated" values in Fig. 10 are explained on page 22ff. Considering the fact that for a true albedo of 80% the measured value with silicon cells would be 89%, it turns out that an estimate of the absorbed radiative energy would be about one half of the true value. Hence, at these high reflection values the knowledge of the right values is of considerable importance.

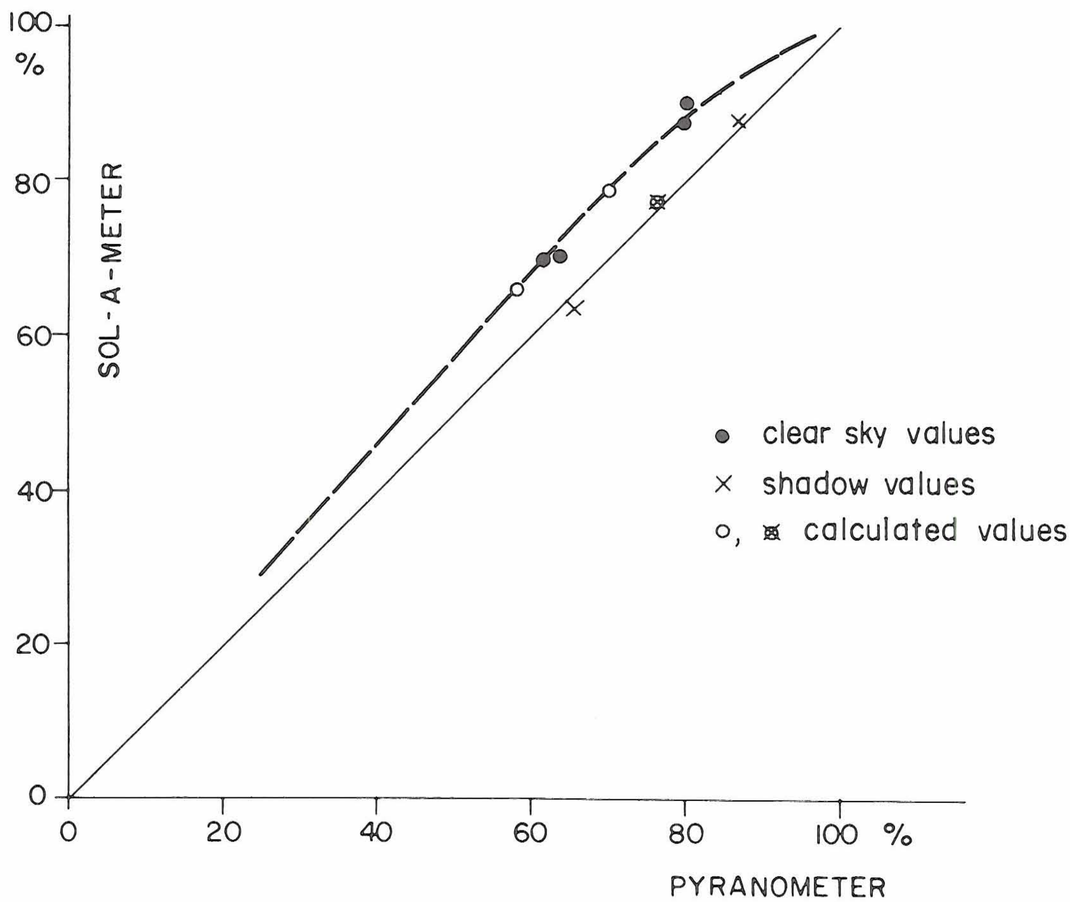

Fig. 10
Comparison of albedo readings with pyranometer and Sol-A-Meter for snow cover. Circles are calculated values (see part IV).

These results can be explained well by the spestral characteristics of the silicon cell, which shall be done in the next chapter.

4. THEORY AND ANALYTICAL RESULTS

Albedo can be defined as:

$$a = \frac{\int_{0.2}^{3\mu} r_\lambda \, f_\lambda \, d\lambda}{\int_{0.2}^{3\mu} r_\lambda \, d\lambda} \qquad (1)$$

where a = albedo

r_λ = spectral reflectivity of surface

f_λ = spectral incoming flux from sun and sky.

This value, "a", is often considered to be a constant, but it can be seen from equation (1) that it is not only dependent on the spectral characteristic of the surface, but also on those of the incoming short wave radiation from the sun and the sky. And this initial radiation is not at all of constant spectral characteristic. While the spectrum of the solar and sky radiation (global-radiation) shows only small variation, the spectral characteristic of cloud-covered sky and of the radiation from the clear sky alone (in the shadow) is considerably different. (See also Fig. 11).

According to these variations in the incoming radiation, all surfaces with pronounced spectral characteristics have to change their albedo with weather conditions. Thus, we cannot expect the albedo to be a constant. Some of the variance of the values found in the literature are caused by this fact.

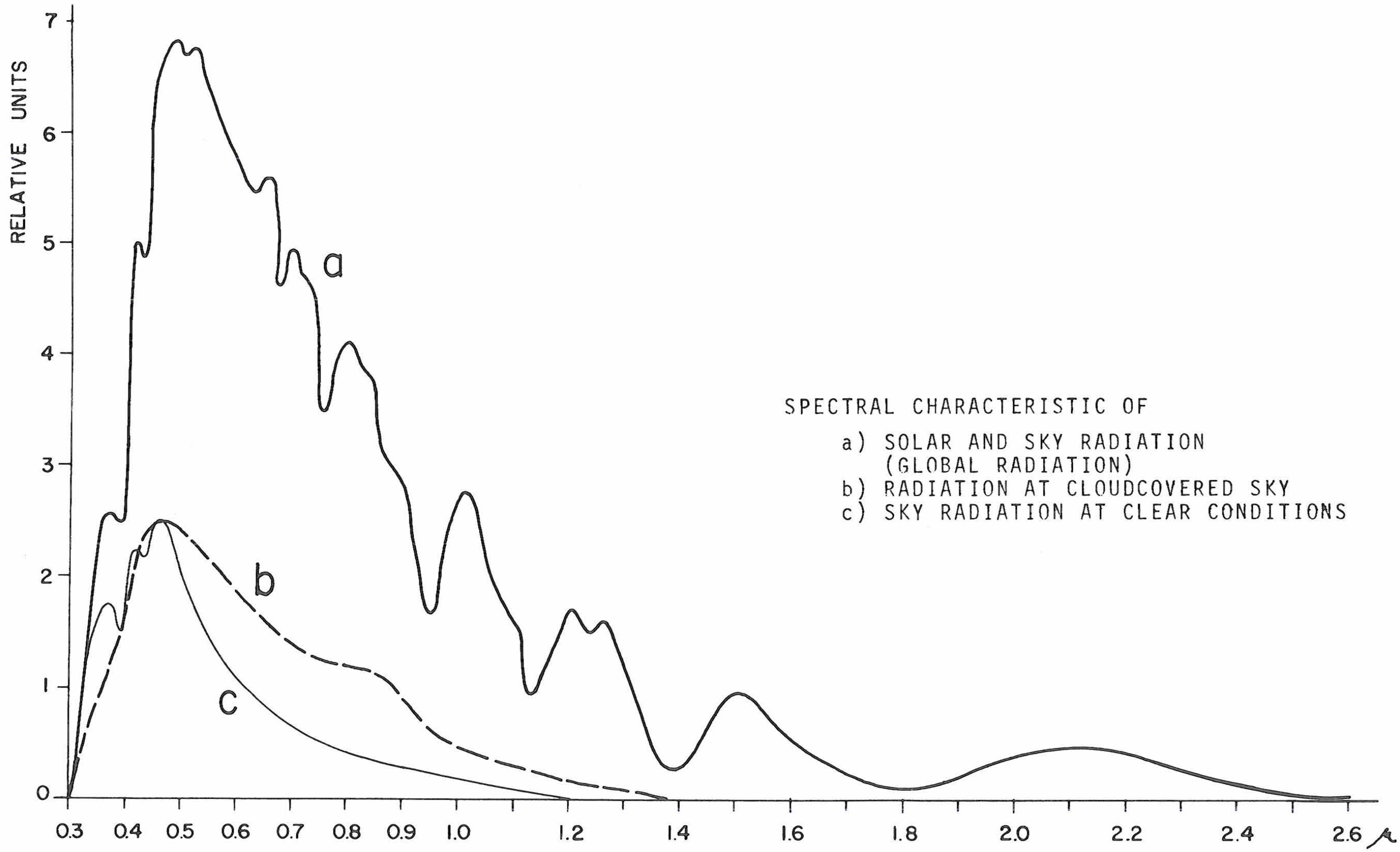

Fig. 11
Spectral characteristic of global radiation at clear sky (a), cloud covered sky (b), and at clear sky in the shadow (c).

Deviations are also caused by the properties of the instruments in use. For practical purposes we have to take into consideration the spectral response of the measuring device:

$$a' = \frac{\int_{0.2}^{3\mu} r_\lambda f_\lambda \phi_\lambda \, d\lambda}{\int_{0.2}^{3\mu} f_\lambda \phi_\lambda \, d\lambda} \qquad (2)$$

where ϕ_λ is the spectral response of the instrument. In the case of an instrument with "flat" response (like pyranometers) ϕ_λ = const. = ϕ and

$$a' = \frac{\int_{0.2}^{3\mu} r_\lambda f_\lambda \phi_\lambda \, d\lambda}{\int_{0.2}^{3\mu} f_\lambda \phi_\lambda \, d\lambda} = \frac{\phi \int_{0.2}^{3\mu} r_\lambda f_\lambda \, d\lambda}{\phi \int_{0.2}^{3\mu} f_\lambda \, d\lambda} = a \quad (3)$$

only with these instruments are we able to obtain "true" albedo values. If ϕ is a function of the wavelength $\phi_\lambda = \phi\ (\lambda)$, as with silicon or selenium cells, then $a' \neq a$. In order not to confuse comparative considerations of this highly important factor in radiation and heat budget, the results obtained with such instruments should not be called "albedo". However, if direct measurements with an instrument of spectral response turn out to give the same results as pyranometers, these instruments can be used to collect "true" albedo data.

As pointed out in the previous chapter, this is the case for silicon cells for all natural surface materials except snow. To prove these experimental results we try to solve equation (1) and (2) for the pyranometer and the Sol-A-Meter respectively.

The functions f_λ and r_λ, spectral incoming radiative flux and spectral reflectivity of some natural surface materials are given in Fig. 11 and 12 (Dirmhirn, 1964). Fig. 13 shows the spectral

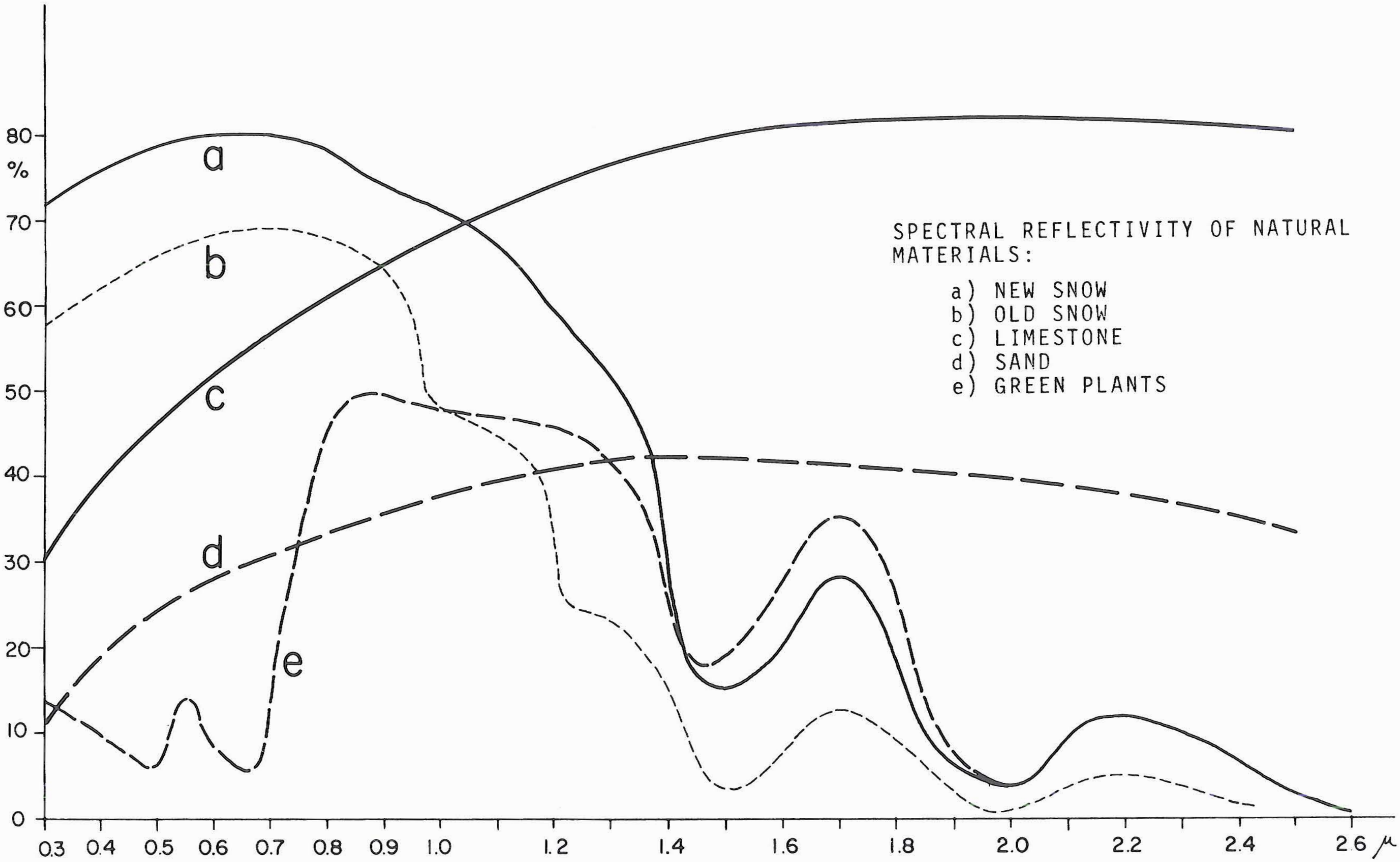

Fig. 12
Spectral characteristic of some natural surface materials: fresh fallen snow (a), old snow (b), limestone (c), sand (d), and green plants (e).

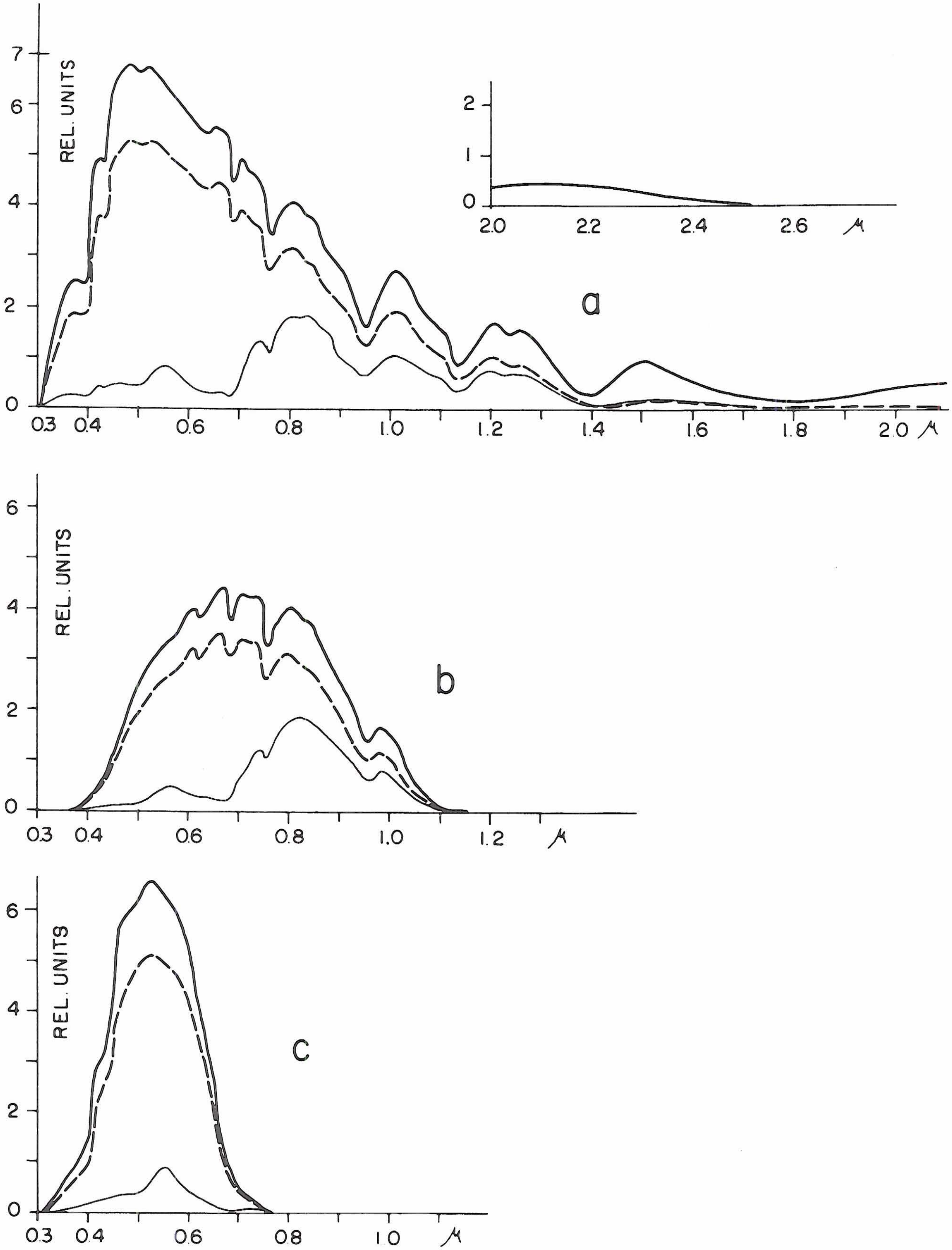

Fig. 14
Spectral distribution of the incoming and reflected radiation from snow and green plants, detected with pyranometers (a), silicon cells (b) and selenium cells (c).

The calculated values from Table 2 are plotted on the graph in Fig. 8 and 9 (values in circles). They fit perfectly into the results from the measurements, thus explaining the difference in the readings of both instruments entirely as an effect of the spectral response of the silicon cell.

5. CONCLUSIONS

As shown by the instrument comparisons in Fig. 8 and 9, the silicon cell can well be used for atmospheric reflection measurements of almost all natural surface materials, such as stones, sand and water. The albedo of green plants is indicated slightly too high with the Sol-A-Meter, but the detected difference of two percent may well be accepted.

However, the albedo of snow fields cannot be determined with either silicon cells or with selenium cells, because they give values that are far too high. The same should be true for the albedo of cloud covers, but comparative measurements have not been made so far.

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