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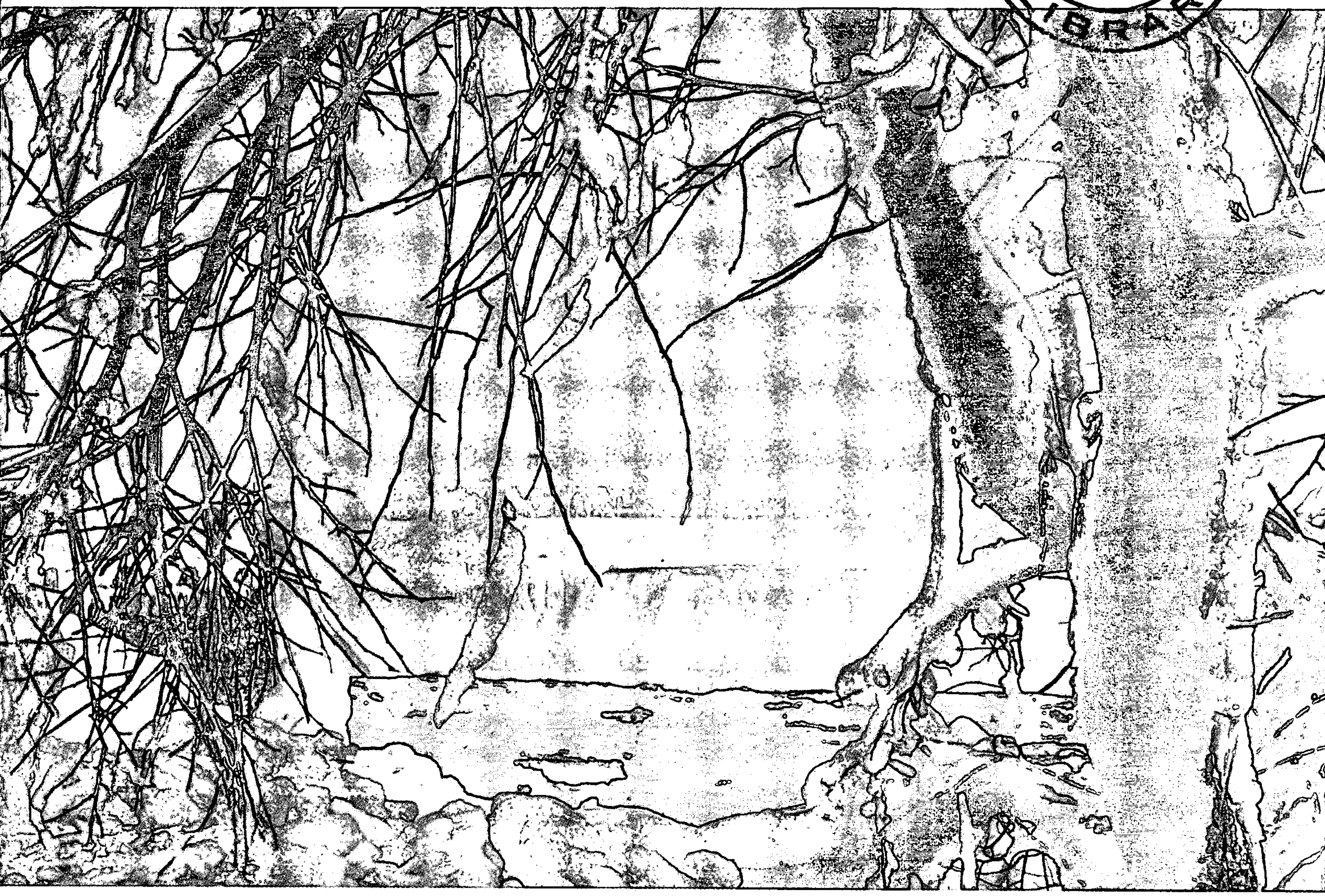
Low Temperature Adapted Submersible Spectrophotometers for Use in Floating Ice Research

W.A. Adams and P.A. Flavelle



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(Résumé en français)

*INLAND WATERS DIRECTORATE,
WATER RESOURCES BRANCH,
OTTAWA, CANADA, 1978.*

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Abstract

The calibration and operation of underwater spectrometers in the visible region (400 nm to 750 nm) are described. The application of the spectrometers for the measurement of the penetration of solar radiation through floating ice is presented with examples of systems used for a variety of ice conditions. The methods used for handling the data, both analog and digital, are given. Also discussed is the role of these spectroscopic techniques in glaciological and limnological studies.

Résumé

Le rapport décrit le fonctionnement et l'étalonnage des spectromètres submersibles servant à l'étude du rayonnement visible (longueurs d'ondes comprises entre 400 nm et 750 nm). Il étudie l'application des spectromètres à la mesure de la pénétration du rayonnement solaire à travers les glaces flottantes et donne des exemples des dispositifs utilisés pour divers états de la glace. Il indique aussi des méthodes de traitement des données, analogiques et numériques. Il examine enfin le rôle des techniques spectroscopiques dans les études de glaciologie et de limnologie.

Low Temperature Adapted Submersible Spectrophotometers for Use in Floating Ice Research

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INTRODUCTION

Floating ice is usually characterized by its thickness and its visual appearance, e.g., in the case of lake ice the terms "black ice" and "white ice" are often used to differentiate between clear bubble-free ice and ice containing a high concentration of air. The detailed formation history of an ice cover can be determined by the stratigraphy investigation of the crystal structure of vertical ice cores. Such studies indicate that there are major differences in the structure of floating ice, depending on the salinity of the water and the conditions of ice formation. Ice observers are trained to make a visual determination of the thickness and age of ice based on its appearance from ice patrol aircraft. Although such an approach is highly subjective, its success must be due to the existence of classes of spectral signatures that are characteristic of the different classes of ice covers. Improved generalization from direct observation making use of remote sensing techniques requires that more quantitative data be collected from ground-based field observations.[1] In addition, limnologists and biological oceanographers are becoming more concerned with the productivity of ice-covered waters. The extent to which light levels and the spectral distribution of light under the ice cover (and within the ice cover) are limiting factors in aquatic plant growth has become an important area of investigation.

This report describes two commercially available spectrophotometers and the methods by which they have been adapted for glaciological investigations of floating ice. The literature concerning light penetration through sea ice has been reviewed by Adams (1975) and that concerning light penetration through lake ice, by Maguire (1975*a*). Although several spectrophotometers have been built for underwater optical studies, only the systems described by Roulet, Maykut and Grenfell (1974) were specifically designed for under ice spectral irradiance measurements. Previous investigations of light transmission through ice and snow reported by Adams (1975) and Maguire (1975*b*) were based on instrumentation that measured the diffuse spectral irradiance.

Two measurement systems are described in this report. One system is designed for characterizing the vertical optical properties of the ice cover. The other is designed to investigate horizontal variations in the optical properties of the ice cover. Both systems were developed and used in field projects during the winters of 1975-76 and 1976-77. The vertical system was employed in both southern Ontario on lake ice about 50 cm thick and the area of Inuvik, N.W.T., on lake ice about 2 m thick. The horizontal system was tested only in southern Ontario during the winter of 1976-77. A quanta spectrometer (QSM 2400, made by A and B Incentives, Sweden) was obtained from Canada Centre for Inland Waters (CCIW), Burlington, for work during the winter of 1975-76. This quanta spectrometer is not as well adapted to cold weather operation (it utilizes an aqueous $CuSO_4$ solution filter) and has a less convenient surface meter than the new quanta spectrometer used during the winter of 1976-77 (QSM 2500, made by Techtum Instruments, Sweden). Results obtained by CCIW with the QSM 2400 in the Great Lakes have been reported by Thomson and Jerome (1975).

DESCRIPTION OF APPARATUS

Quanta Spectrometer QSM 2500

The quanta spectrometer was manufactured for this project by Techtum Instruments, Umeå, Sweden, to meet the specifications listed in the following five tables.

[1] This fact has been recognized by others: Campbell *et al.*, 1974; Campbell *et al.*, 1975; Ramseier and Weaver, 1974.

Optical unit	Remarks
Monochromator	Interference wedge filter
Wavelength range	400 nm to 740 nm
Wavelength accuracy	±4 nm
Half-power bandwidth	15 nm to 18 nm
Scanning*	Bidirectional, full wavelength range, 60 s with special motor selected for operation to −10°C
Field of view	180° cosine corrected
Detector	Silicon photo divide
Electronics*	Chopper stabilized preamplifier connected in photovoltaic mode with operation to −10°C

*Special non-standard feature of QSM 2500 ordered for this project (Fig. 1).

Quanta meter	Remarks
Sensitivity	8 ranges (1, 3, 10, 30, 100, 300, 1000, 10,000) x 10^{15} quanta $m^{-2} \cdot s^{-1} \cdot nm^{-1}$ full scale; equivalent to 4 x 10^{-4} to 4 $W \cdot m^{-2} \cdot nm^{-1}$ at 500 nm; or approximately full moonlight to two times bright sunlight
Recorder output	0 to 100 mV, all ranges
Temperature range	0 to 40°C
Calibration	Better than ±10% throughout whole wavelength range, absolute values

Integrator	Remarks
Sensitivity	8 ranges (1, 3, 10, 30, 100, 300, 1000, 10,000) x 10^{18} quanta $m^{-2} \cdot s^{-1}$ full scale
Recorder output	0 to 100 mV, all ranges

Power supply	Remarks
Batteries meter case	Mercury types 2 x 2.7 V and 4 x 8.1 V
Separate battery case*	Mercury types 4 x 2.7 V and 8 x 8.1 V
Durability	30 h continuous at 20°C

*Special non-standard feature of QSM 2500 ordered for this project (Fig. 1).

Underwater housing for optical unit	Remarks
Material and construction	Cast aluminum with O-ring seal for depths to 100 m
Connecting cable*	Multilead, watertight connectors with 50-m or 100-m cables connected to side of underwater housing to permit sensing head of housing to be placed flush with ice surfaces

*Special non-standard feature of QSM 2500 ordered for this project (Fig. 1).

Under Ice Spectrometer Mounts

Sled

To enable measurements of the horizontal variation of light below the ice, a sled was built in which the underwater spectrometer could be placed (Fig. 2). This sled provides a slight positive buoyancy that holds the spectrometer against the lower surface of the ice sheet permitting it to be moved easily between two holes by means of guide ropes under the ice (Fig. 3).

Figure 1. QSM 2500 with (a) optical unit; (b) quanta meter; (c) integrator; (d) battery pack; (e) underwater housing.

Under Ice Extension Arm

Initial measurements of under ice spectral irradiance were made by lowering the spectrometer by a rope attached at one end through a 25-cm (10-in.) hole in the ice cut by a power ice auger and then by supporting it with a second rope in a horizontal plane by a yoke that

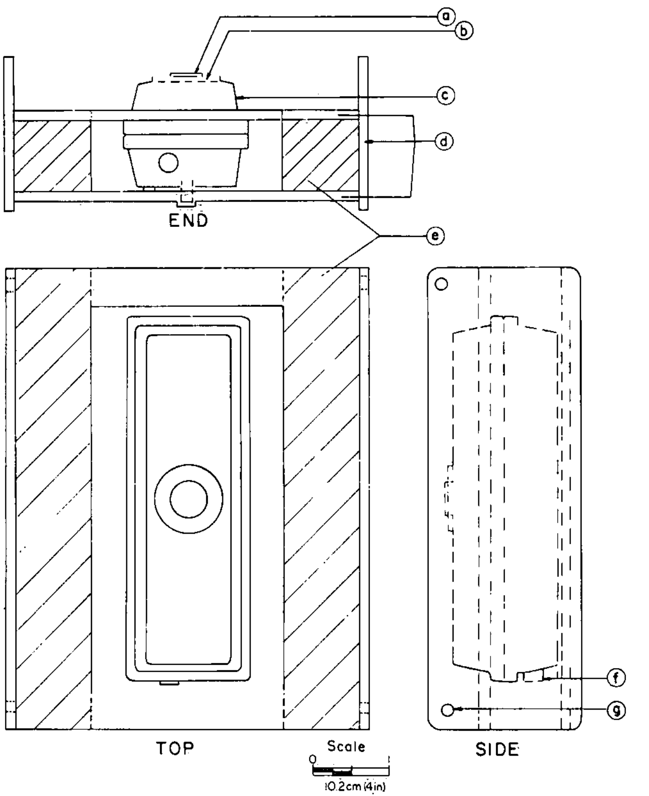

Figure 2. Under ice instrument slider: *a*—light diffuser; *b*—cosine corrected light collector; *c*—QSM 2500 underwater housing; *d*—1.3-cm (0.5-in.) thick plywood finished flat black; *e*—Styrofoam floatation; *f*—underwater cable connection; *g*—hole for guide tow rope.

was attached at each end. Disturbance of the ice cover by hole drilling and other activities in the immediate vicinity of the hole, however, made it desirable to develop a support system to enable the spectrometer to be placed through a hole of the same size, but then displaced horizontally away from the disturbed area near the hole. Figure 4 is a sketch of the support built for this purpose. In Figure 5, the spectrometer is shown attached to the support arm deployed through an ice sheet. Figure 6 shows the spectrometer mounted on the support arm.

Surface Incident Irradiance

Spectral Irradiance

A second QSM 2500, also mounted in an underwater housing, was used during the 1976-77 field season to obtain a simultaneous record of the surface incident spectral irradiance during under ice measurements. This spectrometer, being exposed in the air to much lower temperatures than the immersed unit, was kept warm with a waterproof electric heating pad ("battery blanket" from the Canadian Tire Corp.) in an insulated box (Fig. 7).

Diffuse Spectral Irradiance

Only one quanta spectrometer was available for the 1975-76 winter field program. Surface incident irradiance was monitored with a quantum sensor described by Adams (1975). With this system, the field work was restricted to days of constant daylight conditions, i.e., continuous overcast or cloud-free conditions.

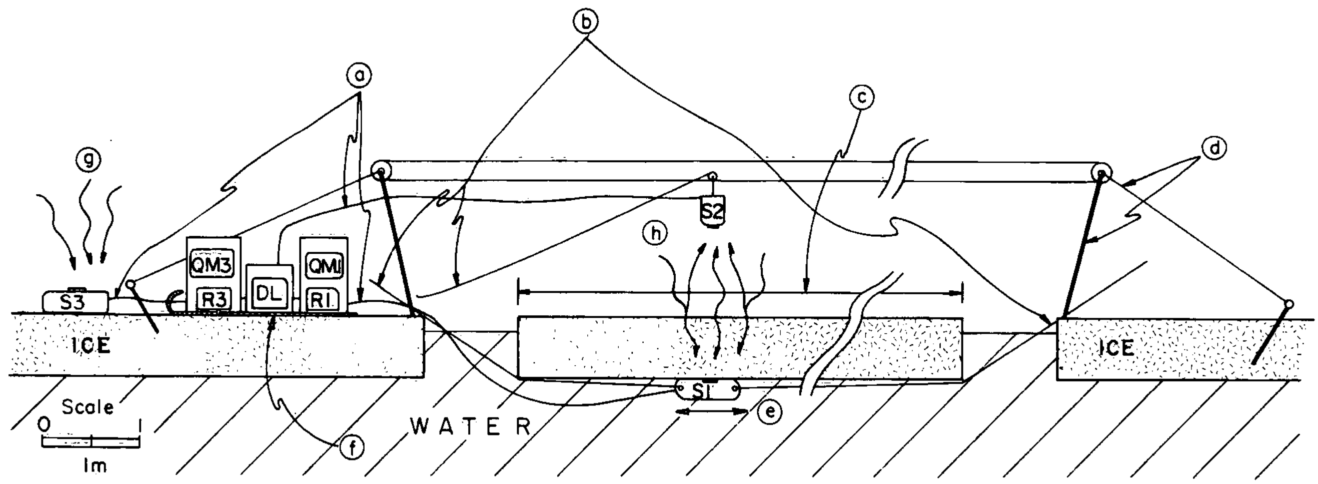

Figure 3. Under ice horizontal light variability experiment: *a*—power and output cables; *b*—position control lines; *c*—extent of virgin ice surface on lake (100 m by 30 m); *d*—pulley system support; *e*—direction of under ice instrument slide; *f*—sled-mounted instruments in heated, insulated boxes; *g*—incident radiation; *h*—incident and reflected radiation; *S1*—QSM 2500 underwater spectrometer; *S2*—Bausch & Lomb "minispec 20" spectral albedo meter; *S3*—QSM 2500 incident radiation spectrometer; *QM1* and *QM3*—quantum meters for *S1* and *S3*; *R1* and *R3*—dual-channel strip-chart recorders for *S1* and *S3*; *DL*—digital tape cassette data logger.

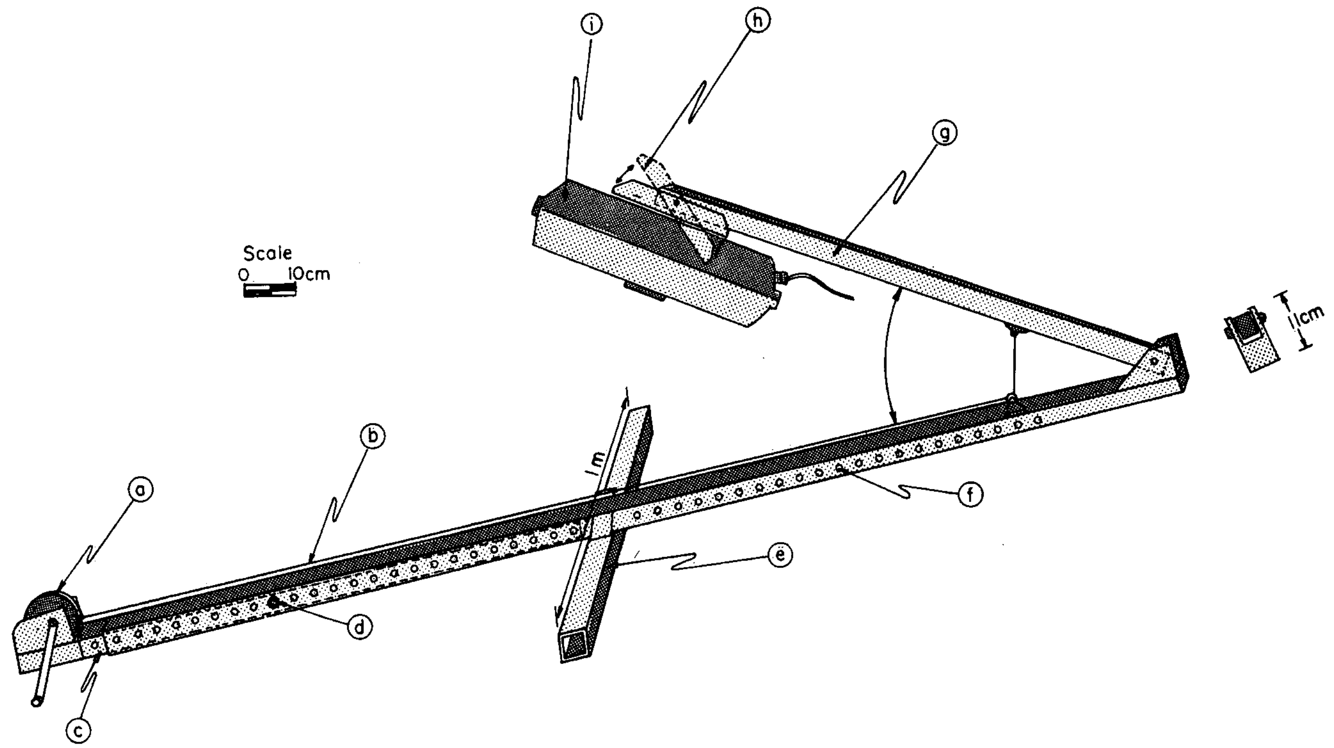

Figure 4. Under ice spectrometer support constructed from aluminum channel painted flat black: *a*–boat trailer winch; *b*–steel cable; *c*–inner extension; *d*–inner extension position pin; *e*–movable ice brace; *f*–positioning holes for mounting brace; *g*–hinged arm; *h*–pivoting spectrometer mounting bracket; *i*–QSM 2500 underwater spectrometer.

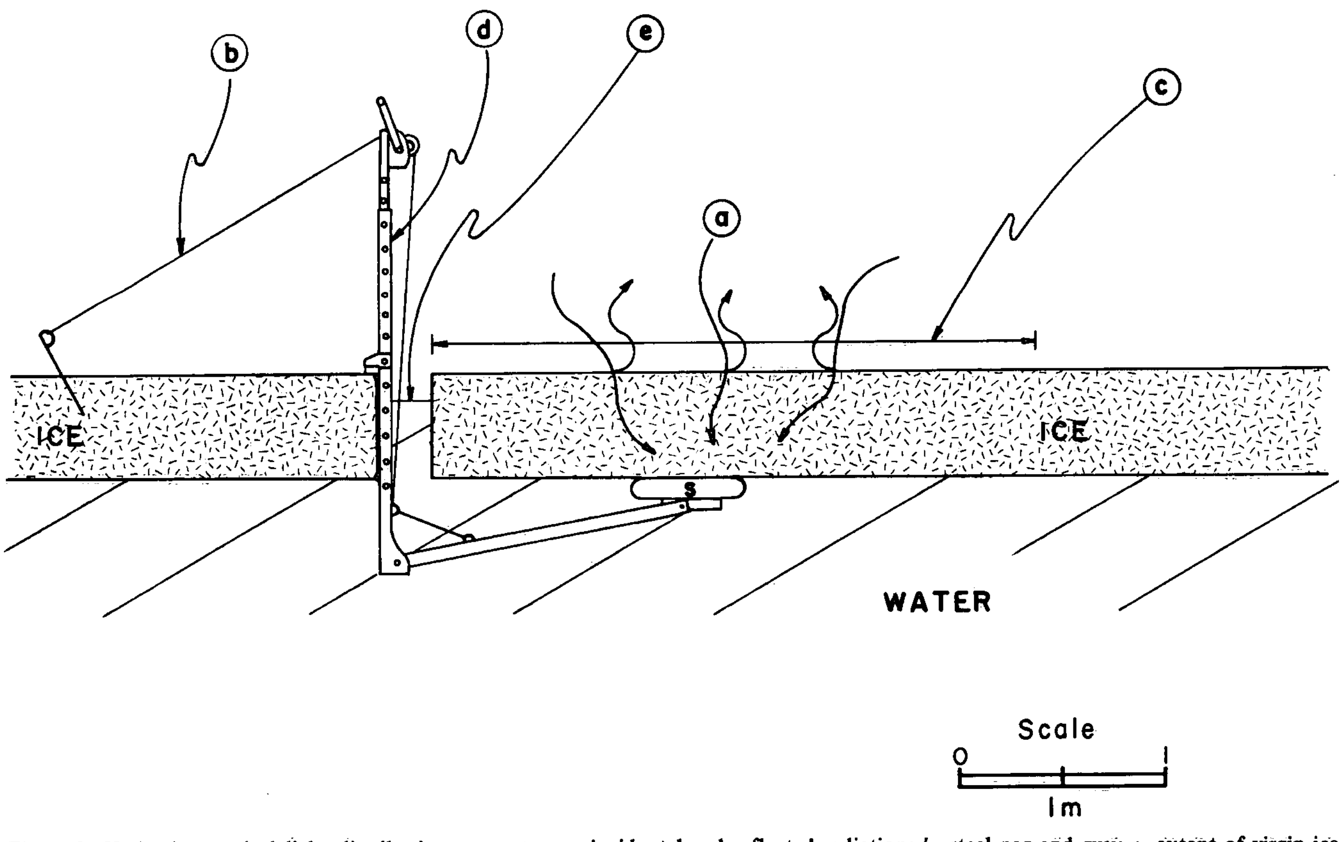

Figure 5. Under ice vertical light distribution apparatus: *a*–incidental and reflected radiation; *b*–steel peg and guy; *c*–extent of virgin ice surface on lake (3 m by 3 m); *d*–under ice spectrometer support; *e*–25-cm (10-in.) diameter hole; *s*–QSM 2500 underwater spectrophotometer.

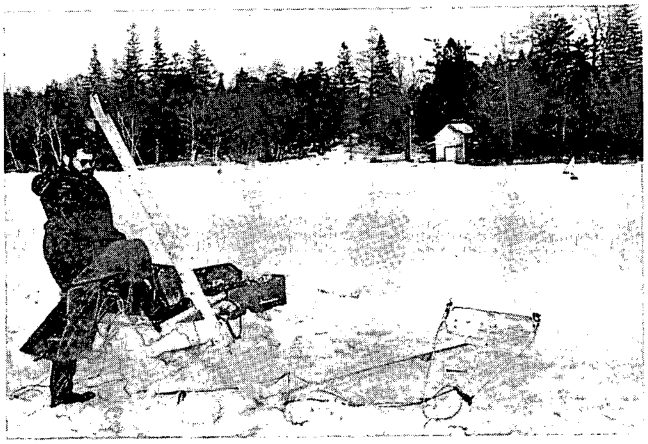

Figure 6. P. Flavelle, Glaciology Division, at Lake St. George, Ontario, with QSM 2400 mounted on the support arm. (The support was painted flat black following the tests conducted at the time of this photograph.)

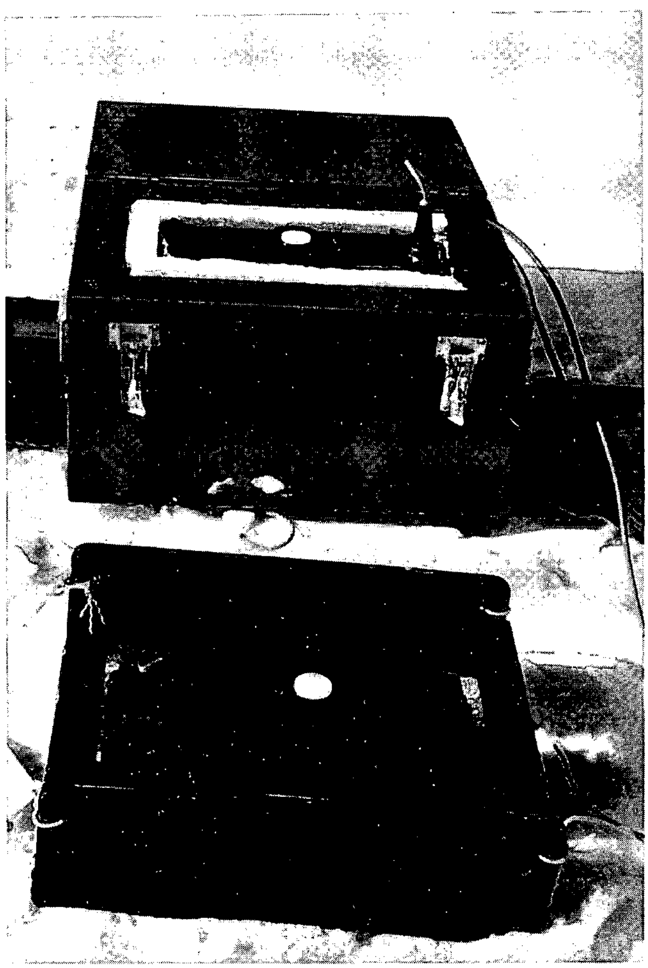

Figure 7. Sled irradiance spectrometer and surface incident irradiance spectrometer in heated, insulated housing.

Albedometer

Optical

A Bausch & Lomb "minispec 20" spectrophotometer (Fig. 8) was adapted for irradiance measurements by replacement of the standard tungsten lamp source with a Plexiglas light pipe to collect and direct light to be measured into the monochromator. The specifications of the spectrophotometer are:

Monochromator type	Diffraction grating
Wavelength range	400 nm to 700 nm
Wavelength accuracy	±3 nm at 546 nm
Wavelength readability	1 nm
Nominal bandpass	20 nm
Photometric reproducibility	±2% full scale
Power supply	5 V dc
Operating temperature	+5°C to -40°C
Output (0 to 100% full scale)	0.5 V dc
Detector (Clairex type No. 9 CdS photo resistor)	Linear response one decade above and below meter range; peak response in blue

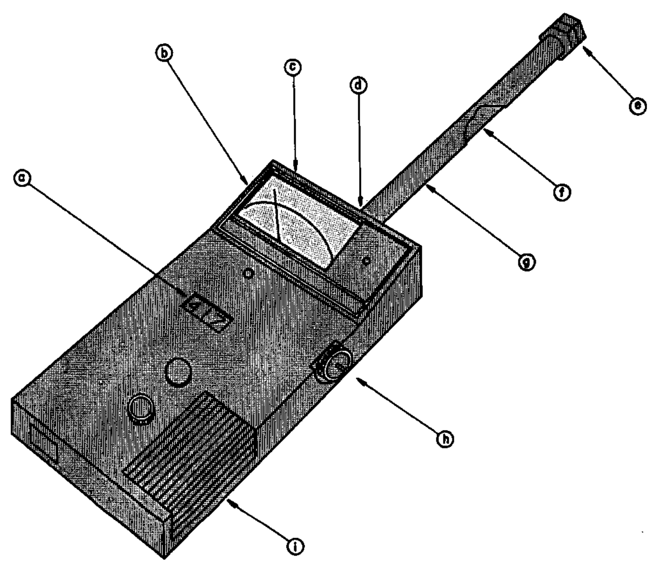

Figure 8. Bausch & Lomb "minispec 20" adapted for irradiance measurements: *a*—wavelength readout to 1 nm; *b*—meter reading "percent transmission" (not used); *c*—power 6 V dc and output from 0 to 500 mV; *d*—tungsten lamp light source removed to accept light pipe; *e*—screw-on Teflon diffuse-type light collector for cosine response; *f*—acrylic plastic light pipe insert; *g*—brass light-tight tube; *h*—wavelength control knob with flexible linkage to outer control knob on insulated outer case (see Fig. 9); *i*—detector (sample) compartment.

Low Temperature Case

Since the spectrophotometer is used outside at low temperatures and under wet conditions, an insulated protective case has been constructed (Fig. 9). This case does not have to be opened to turn on the albedometer because with external power it can be left on continuously. The wavelength can be adjusted with the external control knob. No modification for automatic scanning has been attempted, although such a feature could easily be added. The Teflon diffuser has been designed for removal and replacement by a fibre optics cable to permit measurement of irradiance within a snow pack with minimum disturbance of its structure.

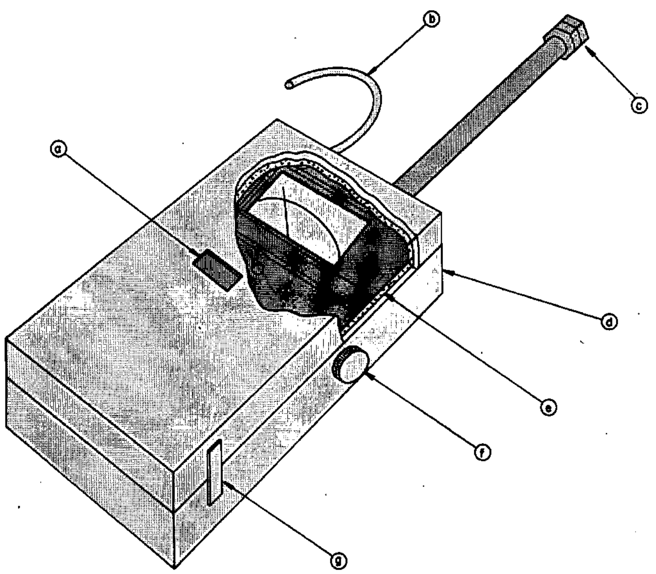

Figure 9. Albedometer low-temperature case: *a*—wavelength readout light pipe; *b*—power, output, and thermistor cable; *c*—Teflon light diffuser probe fitting adaptable to 2-m fibre optics probe; *d*—outer container, plywood (1 cm) with flat black finish; *e*—inner insulation from Styrofoam with electric heater and thermistor temperature sensor; *f*—wavelength control knob; *g*—case fastener on hinged lid.

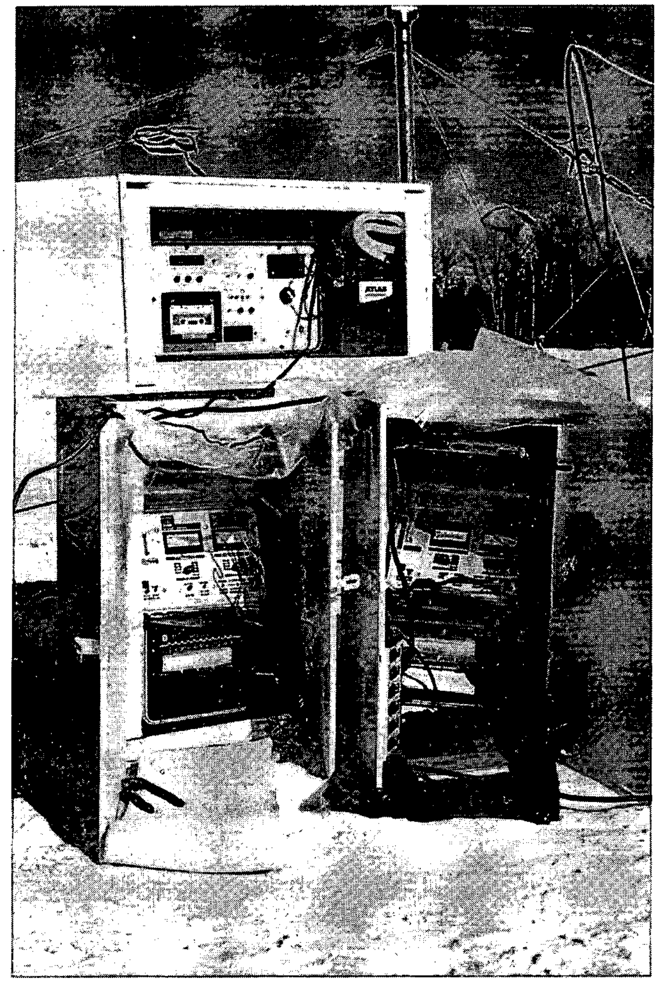

Figure 10. Field equipment shelters containing two quanta spectrometer surface units, 12-V Ni-Cd battery power supply for albedometer and albedometer heater, digital tape cassette data logger and 12-V lead-acid battery, and digital multimeter for measurement of albedometer output and temperature.

Field Equipment Housing

The spectrometer quanta meters and recording equipment were protected from the environment and kept warm in well-insulated plywood cases heated with electric heating pads (Fig. 10). The equipment was moved on toboggans.

CALIBRATION

Apparatus to Calibrate Irradiance Sensors

The source used was a quartz-iodide standard lamp (No. QI 111), calibrated by the Optics Section, Division of Physics, National Research Council of Canada (Report No. P.O. -207). It was powered by a Deltron regulated dc power supply; a 0.01-ohm calibrated resistor, Model 9200 from Guildline Instruments, was used in series with the lamp to measure the current passing through the circuit. The potential across the resistor was measured using a Hewlett-Packard Model 3450 voltmeter with a 10-mV potential drop corresponding to a current of 1.0 A. The lamp was mounted vertically (i.e., plumb), with its centre 32.2 cm above an optical track. Six centimetres along the track from the lamp filament was an optical baffle, 66 cm by 66 cm, painted flat black, with a 1.3-cm wide and 2-cm high aperture, aligned with the lamp. Twenty-six centimetres from this baffle was a second baffle, 33 cm by 33 cm, with a circular aperture 9 cm in diameter. This aperture was aligned with the first aperture and the lamp. The underwater light sensing unit of the spectrometer to be calibrated was placed 18 cm beyond the second baffle. Stray light and backscatter were reduced by enclosing the calibration apparatus in black cloth. The total distance from the diffuser of the spectrometer to the lamp filament was 50 cm ±0.2 cm. Spectra were recorded scanning in both directions (400 nm to 700 nm, and 700 nm to 400 nm).

Wavelength Calibration

The calibration apparatus was modified in order to calibrate the wavelength response of the spectrometers. To process data from the QSM 2400, it was first assumed that the limits of the scan were 400 nm and 720 nm and that the rate of scan was constant during any one run. With these two assumptions a spectrum was divided equally into 32 increments, and the pen deflection was read every 10 nm, from 400 nm to 720 nm. These assumptions were checked as follows.

The second baffle on the optical track was removed and replaced by a Jarrell-Ash Minichromator, Model 82-405, with its exit slit removed (this was to allow sufficient radiation to exit to get a response from the QSM 2400). The Minichromator was positioned as closely as possible to the aperture of the first baffle, and the QSM 2400, as closely as possible to the Minichromator. Absolute intensities were not of concern, since it was necessary to obtain a minimum intensity sufficient to get a response from the QSM 2400. The entrance slit was 100 μm. The equipment was aligned using a small helium-neon laser beam that passed through the Minichromator at a setting of >632.5 nm and <633.0 nm (the helium-neon line was 632.8 nm).

The gain on the QSM 2400 was set at the most sensitive gain (No. 8), and the strip-chart recorder scale was set at 10 mV per half-scale deflection (2 mV per chart paper division). Spectra were recorded, scanning in both directions, for Minichromator settings of 700 nm, 650 nm, 600 nm, 550 nm and 450 nm, using the standard lamp QI 111 as a source. The spectra were digitized using a Hewlett-Packard 9830A minicomputer and 9862A calculator plotter, with software based on the X-Y pen translation feature. The data extracted from each spectrum were the proportion of the scan remaining to be recorded once the centre of the band had been reached, after starting from the low wavelength limit of the spectrum. The range of the spectrum was assigned an arbitrary value of unity (1). Plotting the wavelength of each band as a function of its position in the spectrum relative to the limits of the spectrum gave a straight line, permitting the calculation of the limits of the spectra. The results are:

Direction of scan	Lower limit (nm)	Upper limit (nm)
Low to high wavelengths	364.0	722.2
High to low wavelengths	375.6	728.2

The differences in the limits of the spectra scanned in different directions are attributed to a hysteresis loss in the mechanical scanner. The shape of the spectra confirms this, since at the beginning of each spectrum when scanning from high to low wavelengths there is a "flat spot," a small area where there is no response shown by the strip-chart recorder while the scanner drive mechanism engages fully. Assigning different limits to the spectra scanned in different directions corrects this inconsistency. All spectra analyzed for this calibration have been assigned these limits, and the data have been read for the corrected wavelengths.

The wavelength responses of the QSM 2500 underwater spectrometer and the Bausch & Lomb "minispec 20" were also checked. The QSM 2500 has a 0 to 100-mV output proportional to the wavelength from 400 nm to 750 nm. The QSM 2500 was found to meet the wavelength accuracy of its specifications, ±4 nm; therefore spectra recorded in either direction are identical. The "minispec 20" also met its specifications, ±3 nm at 546 nm.

QSM 2400 Intensity Calibration

Four spectra were recorded on each of the gain settings, 1, 7 and 8 (two in each direction). Tables 1 and 2 give the difference between the two repetitions of each setting as a percentage of one of the spectra [i.e., $I_1(\lambda) - I_2(\lambda)/I_1(\lambda)$]. This, being a very small sampling (two samples only), may not be representative, but it gives some indication of the reproducibility of the data. There appear to be no trend-like differences between the variations in data whether recorded scanning from 400 nm to 720 nm or from 720 nm to 400 nm. The only trend easily recognized is the increasing relative variation in the data toward lower wavelengths. This is because the output of the standard lamp is lower by about one order of magnitude at 400 nm than at 720 nm. Hence, a reading error of one half of the thickness of the trace (≃0.01 divisions) will result in a relative error about one order of magnitude larger at 400 nm than at 720 nm.

Table 1. Variation in Spectra Recorded on QSM 2400 from 400 nm to 720 nm (ΔI/I, Percent)

Wavelength (nm)	Gain No. 1 scan 22–scan 24 / scan 22	Gain No. 7 scan 8–scan 10 / scan 8	Gain No. 8 scan 4–scan 6 / scan 4
400	0.000	7.143	4.651
410	0.000	6.000	0.000
420	4.444	3.571	3.509
430	2.000	0.000	1.538
440	1.754	0.000	0.000
450	0.000	1.250	1.190
460	1.389	1.111	0.000
470	1.250	0.980	0.952
480	0.000	4.274	0.840
490	1.000	0.776	0.741
500	0.885	1.379	0.000
510	0.806	1.258	1.227
520	3.521	2.793	0.552
530	0.676	1.047	0.510
540	1.852	0.966	1.422
550	0.575	1.345	0.877
560	0.000	0.000	0.000
570	0.498	1.521	0.746
580	0.935	0.357	1.399
590	0.000	1.333	1.307
600	0.000	1.238	0.304
610	1.132	0.000	0.284
620	0.709	0.552	0.813
630	0.339	1.309	0.513
640	0.651	0.000	0.244
650	0.307	0.709	0.231
660	0.578	0.446	0.000
670	0.546	0.210	0.612
680	1.558	0.199	1.354
690	0.978	0.748	0.909
700	1.367	0.000	0.000
710	0.842	0.485	0.317
720	1.195	0.153	0.000

Table 2. Variation in Spectra Recorded on QSM 2400 from 720 nm to 400 nm (ΔI/I, Percent)

Wavelength (nm)	Gain No. 1 scan 21 – scan 23 / scan 21	Gain No. 7 scan 7 – scan 9 / scan 7	Gain No. 8 scan 3 – scan 5 / scan 3
400	2.778	4.444	0.000
410	2.381	3.922	0.000
420	0.000	1.724	1.667
430	0.000	3.077	0.000
440	1.695	1.370	1.316
450	1.538	1.235	0.000
460	1.389	2.174	1.053
470	1.235	2.913	1.852
480	1.099	1.739	0.000
490	0.990	2.326	0.752
500	1.786	2.083	1.351
510	2.439	3.750	0.000
520	0.000	3.390	0.562
530	0.667	2.578	0.000
540	0.000	2.392	0.000
550	0.575	1.778	0.437
560	0.538	1.235	0.000
570	0.000	1.533	0.382
580	0.935	3.534	0.353
590	0.870	0.997	0.662
600	0.405	1.242	0.308
610	0.755	0.000	0.287
620	0.360	0.274	0.270
630	0.339	0.000	0.256
640	0.649	0.000	0.491
650	0.929	1.190	0.459
660	1.146	0.000	0.647
670	1.609	0.620	0.808
680	0.763	0.592	0.386
690	0.723	0.369	0.541
700	1.121	0.345	0.337
710	0.414	0.160	0.156
720	0.000	0.606	0.295

Table 3 gives the standard deviation, expressed as a percentage of the root mean square (rms) of the data (as a function of wavelength), for each gain setting. Combining the data from scanning in both directions, the trend in the deviations mentioned above is very evident.

The data from the four scans recorded at gain No. 1 were combined to give the calibration curve shown in Figure 11. It is plotted as the root mean square, ±1 standard deviation. Also shown is an earlier calibration done at the Canada Centre for Inland Waters (lower curve). The large difference is due to a different $CuSO_4$ filter solution used for each of the calibrations.

The rms output and standard deviation for the data recorded in gain No. 1 were compared with the calibration value provided by the manufacturer of 5008 x 10^{13} quanta $cm^{-1} \cdot s^{-1} \cdot nm^{-1} \cdot mV^{-1}$ to get the relative response shown in Figure 12.

The spectra recorded at other gain settings were multiplied by the gain factors provided by the manufacturer. The results generally gave agreement with the calibration gain No. 1 obtained with the setting to within one standard deviation of the rms value of the gain No. 1 curve.

QSM 2500 Intensity Calibration

The wavelength and intensity of the irradiance of the National Research Council of Canada standard lamp No. QI 111 set up in the apparatus described on p. 6 were recorded simultaneously from the output of the QSM 2500 on a dual-channel strip-chart recorder (Weather Measure, Model EPR 200S). A quanta meter gain setting of $Q = 300 \times 10^{15}$ quanta $m^{-2} \cdot s^{-1} \cdot nm^{-1}$ full scale was used to record eight scans. In Figure 13, the mean output and mean relative response are plotted

Table 3. Standard Deviation Recorded on QSM 2400 Expressed as a Percentage of the Root Mean Square of Three Sets of Four Spectra

Wavelength (nm)	Gain No. 1	Gain No. 7	Gain No. 8
400	4.252	5.909	2.247
410	5.054	3.466	2.220
420	4.206	3.035	2.882
430	4.020	1.575	1.445
440	3.147	0.692	0.664
450	2.334	1.021	1.136
460	1.134	1.394	0.530
470	1.604	1.272	1.184
480	1.055	1.941	0.419
490	1.284	1.105	0.967
500	0.849	1.192	0.555
510	1.140	1.680	0.868
520	2.085	1.997	0.719
530	0.869	1.239	0.768
540	0.783	1.075	0.708
550	0.331	0.998	0.419
560	0.268	0.522	0.234
570	0.249	0.993	1.040
580	0.537	1.504	1.083
590	0.434	0.742	1.118
600	0.202	0.743	0.727
610	0.777	0.168	0.841
620	0.981	0.611	0.348
630	0.277	0.753	0.246
640	0.420	0.000	0.235
650	0.532	0.580	0.290
660	0.526	0.791	0.513
670	0.844	0.771	0.673
680	0.873	0.525	0.698
690	0.606	1.125	0.764
700	0.746	0.814	0.796
710	0.712	0.772	0.608
720	0.535	0.706	0.612

along with the standard deviation. The effect of using a higher or lower sensitivity setting, Q = 100 or Q = 1000, was tested by running two additional scans at each Q setting and by plotting the combined data. The uncertainty approaches 10% only toward 400 nm in this combined data owing to the lower lamp output at the blue end of the spectrum, as can be seen in the output curve in Figure 13. The overall reproducibility for the QSM 2500 is ±2%. The relative response curve indicates a uniform sensitivity over the spectrum, but that the QSM 2500 reads low by about 40% in absolute quanta response over the spectrum.

A second QSM 2500 underwater quanta spectrometer (on loan from CCIW) was calibrated against the Glaciology Division unit tested with the National Research Council standard lamp. This test was conducted by recording spectra in daylight outside with the units placed horizontally side by side in a shadow-free area. The results are recorded in Figure 14. The CCIW unit had a larger response than the Glaciology unit over the whole spectrum by about 15%.

Angular Response

A collimated light source was set up 1.67 m from the diffuser of the QSM 2500 to measure the effect of variation in the response of the instrument as the angle of incident light was varied from normal to the diffuser. The response curve of the QSM 2500 is shown in Figure 15 [curve (a)]. For comparison, the albedometer was tested in the same manner; the results are also given in Figure 15 [curve (b)]. A flat-black metal shield used to make measurements of light emergent from the ice cover was in place for angles between 0° and 60° and was removed to obtain the response from 60° to 90°, since the shield geometry restricted light from striking the diffuser for angles greater than 60°. Both curves (a) and (b) are close to the curve of an ideal cosine corrected irradiance meter. A small correction in the albedometer measurements for the intensity lost because of the light shield is seen to be necessary.

FIELD OPERATION

Surface

On December 8, 1976, cold tests were conducted under stable cloud-free daylight conditions on the roof of the Sir William Logan Building, 580 Booth Street, Ottawa. The building provides an unobstructed 180° horizon at 112 m above street level. The underwater housing containing the light sensor at an initial temperature of -20°C was exposed to an outside air temperature of -15°C at 13:50 h. Spectra were recorded with the meter maintained inside the rooftop equipment room. The first scan ($\Delta\lambda$ = 340 nm) took 1.05 min (+20°C). One hour later, the sensor unit temperature was -13°C and the scan time was 1.1 min. After two hours, the scan time was 1.6 min at -18°C. These results emphasize the need to record the wavelength during a spectral scan. This is possible with the QSM 2500. Data obtained on strip charts with the QSM 2400 had to be analyzed by division of the wavelength scale into wavelength increments due to the variation of scan time with temperature and battery power. A daylight spectrum recorded at this location by the QSM 2500 is shown in Figure 16.

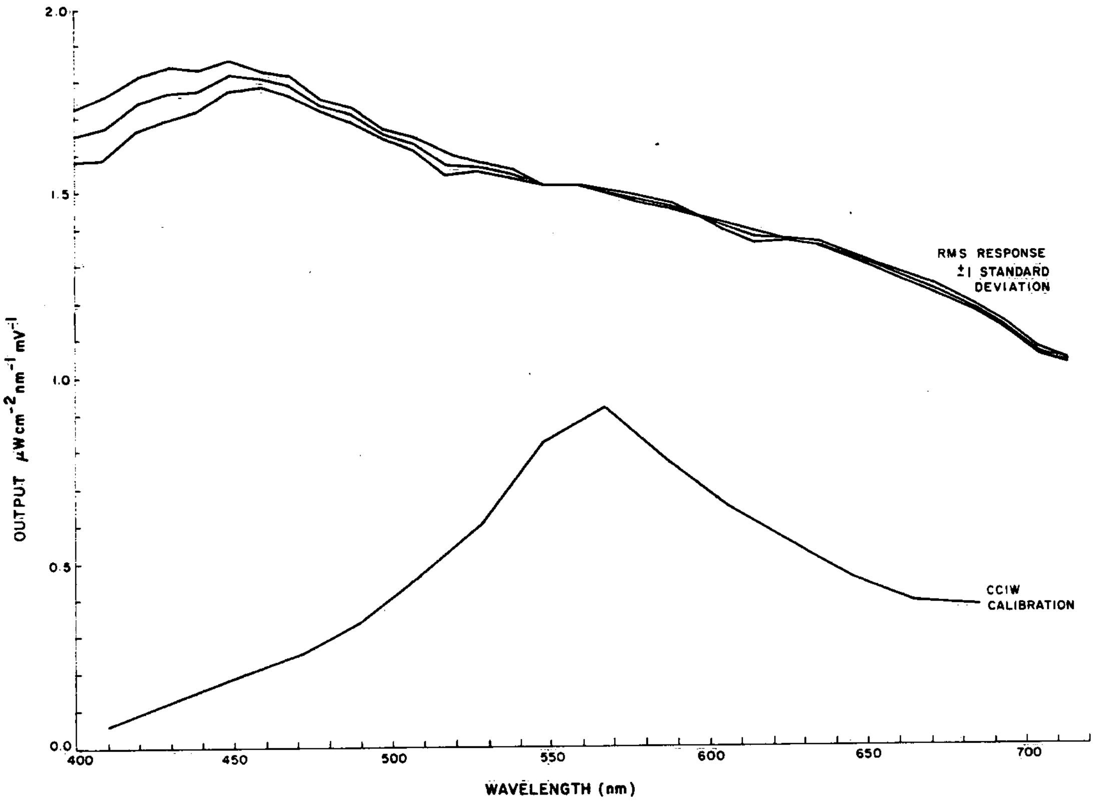

Figure 11. Graph of calibration for QSM 2400, output vs wavelength.

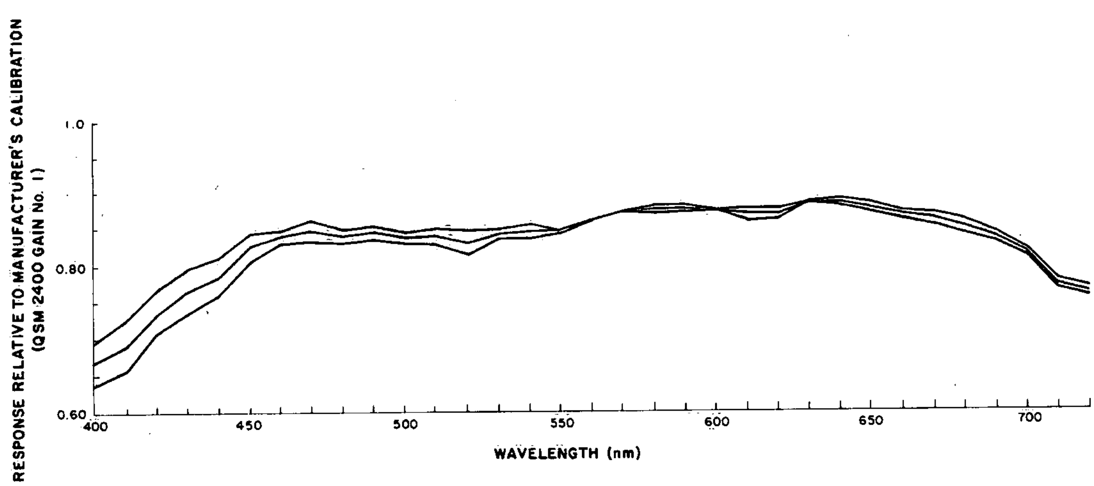

Figure 12. Graph of response of QSM 2400 based on manufacturer's calibration relative to standard lamp calibration as a function of wavelength.

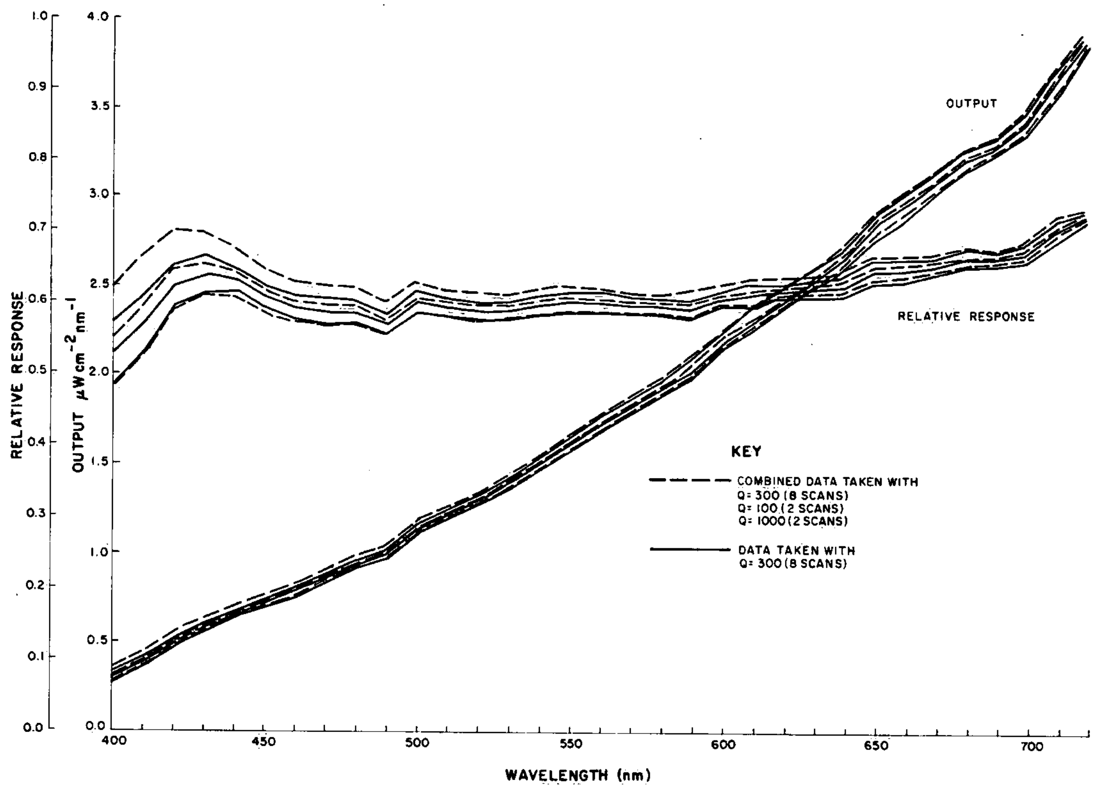

Figure 13. Graph of (a) response of the QSM 2500 based on the calibration provided by Techtum Instruments relative to the standard lamp vs wavelength and (b) output of the standard lamp as measured by QSM 2500 vs wavelength. Solid lines represent data taken on eight scans with $Q = 300 \times 10^{15}$ quanta $m^{-2} \cdot s^{-1} \cdot nm^{-1}$; dashed lines represent eight scans as above combined with two scans with Q = 1000 and two scans with Q = 100.

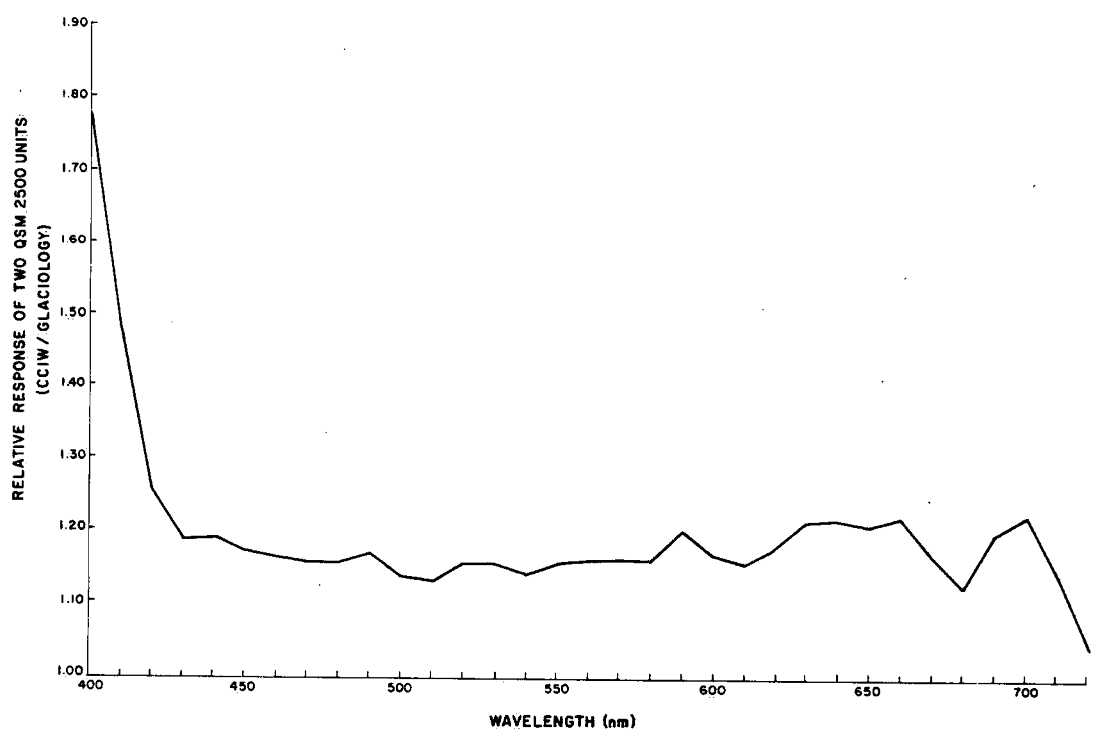

Figure 14. Relative response of two QSM 2500 quanta spectrometers from 400 nm to 740 nm.

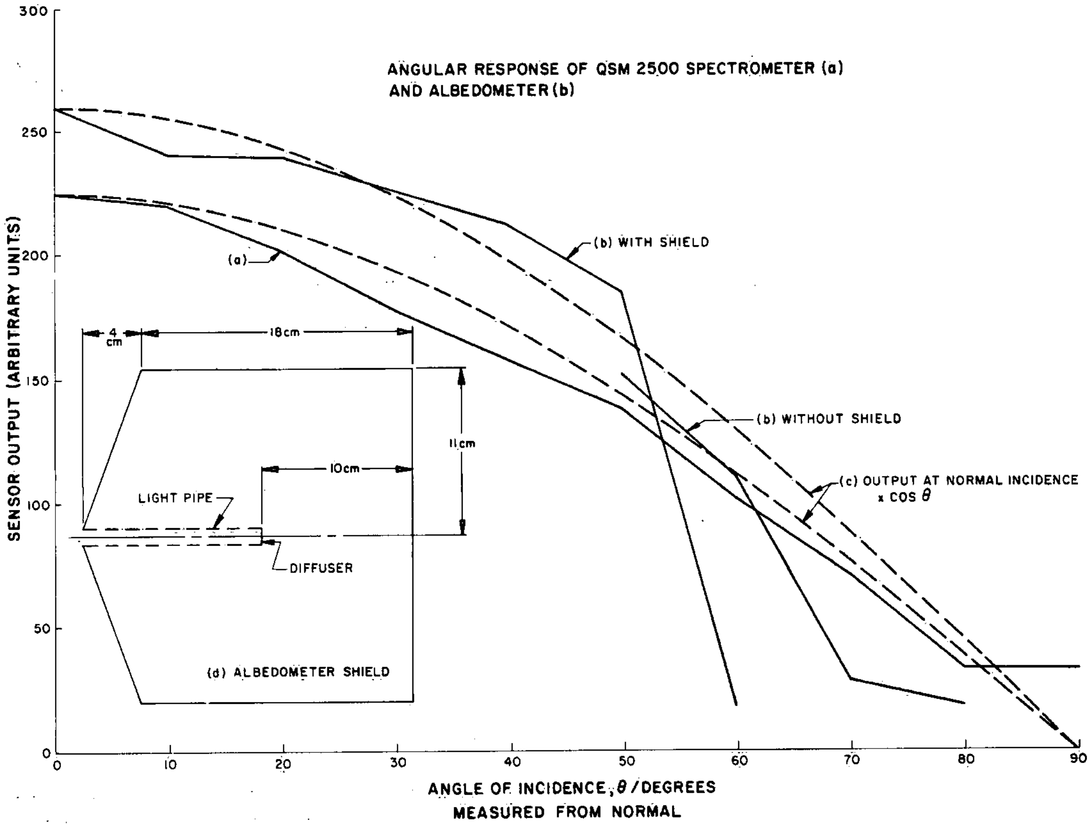

Figure 15. Response of (*a*) the QSM 2500, (*b*) the albedometer, and (*c*) an ideal cosine collector as a function of the angle of incident collimated radiation at 610 nm. The dimensions of the albedometer light shield are indicated in the sketch (*d*).

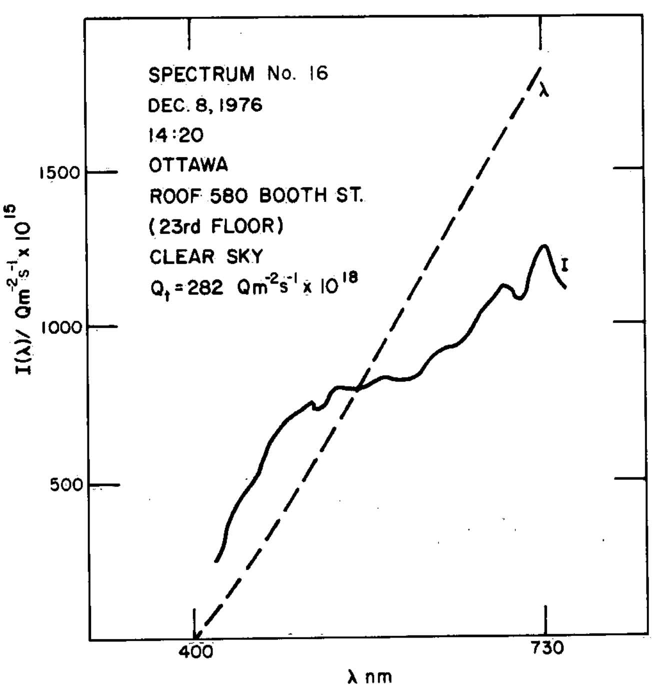

Figure 16. Daylight spectrum recorded by the QSM 2500.

Under Ice Sled Operation

The movement of the sled described on page 2 is made possible by the control lines shown in Figure 3. These lines are placed in the lake prior to freeze-up. They must be weighted down to prevent their freezing into the ice sheet, and adequate marking buoys must be left at each end to permit the location of the control line after the ice cover is strong enough to support field workers. Holes are made with ice chisels and ice augers at each marking buoy to free the control line, with one hole being large enough to launch the sled. The use of a chain saw can speed the hole cutting operation, but the chain lubricant may create problems, as it forms a slick on the water in the hole.

The operation of the sled spectrometer required two people. One person moved the sled short distances from the opposite hole by pulling the control line at measured intervals while the other conducted measurements and documented the spectra. Two measurement methods were tried: (1) the complete spectrum was recorded at fixed under ice locations (of course the surface solar radiation spectrum was recorded simultaneously with any under ice measurements) and (2) the sled was moved from one hole to the other at fixed wavelengths, the irradiance being recorded at a number of fixed intervals between the holes. The second method was generally adopted because it was faster to move the sled under the ice sheet than to scan a complete spectrum at each under ice location (usually 0.5-m or 1.0-m intervals). The sled was removed from under the ice sheet and the buoyant control ropes were weighted from the under ice surface after each day of measurements. Once when this precaution was not taken, a diver had to free the frozen control line under the ice because of the growth of black ice.

In the course of research using the under ice sled, various natural and artificially induced conditions have been brought about on the lake ice sheet. Undisturbed snow has been shovelled off and the surface swept clean by using corn brooms. The effect of a dry and wet ice surface on ice light transmission has been investigated. In addition, studies can be done on the effects on light transmission properties of the ice cover produced by the depth of snow; the crystal type; and the compression of snow by snowmobile operation, skiing or other activities.

Under Ice Extension Arm Operation

The support arm described on page 2 was designed for studying the optical properties of ice sheets less than 0.5 m thick. Under these conditions, the drilling of a suitable hole (25 cm dia.) will disturb the under ice light field in the vicinity of the hole such that tethered operation of the spectrometer will not provide a reliable measurement of irradiance directly under the hole. The effect of the hole on light measurements in thick ice is less serious because of the diffusing nature of the upper ice layers and the smaller ratio of hole diameter to ice thickness.

The extended support arm, with the spectrometer attached, is lowered into the water through the hole drilled in the ice to the ice brace, and then the winch is used to haul the lower arm to a marked cable position which places the spectrometer under the ice in an orientation parallel to the lower ice surface. The ice brace is attached to the main beam in such a location that a guy line pegged into the ice will maintain the spectrometer in this position during measurements. To measure irradiance in the water column below the ice sheet, the ice brace is attached to locations higher up the main beam. The advantage of this under ice support system is that the ice surface through which radiation is being measured is unaffected by the hole drilling operation and that the light cone below the hole is not detected by the spectrometer (Fig. 5).

Operation of Albedometer

The albedometer is used to measure the irradiance upwelling from the ice surface. To accomplish this, the spectrometer in its protective case, described in the section entitled "Albedometer," was suspended above the ice surface with a pulley system (Fig. 3). Using this system, the surface can be investigated without damaging the delicate snow structure by raising and lowering the albedometer from outside the test area. Measurements from one end of the test area to the other can be made by pulling the albedometer along the support cables.

Measurements were made with a digital voltmeter through a multiple conductor cable attached to the albedometer and fastened loosely to the pulley support cable. Also connected with the multiple conductor cable was a thermistor to monitor the housing temperature, power for an electric heating element, and power for the spectrometer. A NiCd battery was used for a power supply. The temperature was regulated manually by applying voltage from 0 to 14 V from the battery, as necessary.

DATA HANDLING

Data Recording

The spectra from the surface and subsurface spectrometers are recorded on two strip-chart dual-pen recorders (for intensity and wavelength) or intensities for fixed wavelengths are recorded in a lab book directly from the surface meters. The spectra can also be recorded on magnetic tape cassettes, which provide a digitized record consisting of 160 data points per min. This results in a record consisting of approximately 40-wavelength and 40-irradiance points per spectrum. This digital cassette tape data logging system has been described by Adams and Flavelle (1978).

Data Processing

The data are transferred to digital forms with a Hewlett-Packard 9830 calculator system by means of a program making use of the X-Y translation feature of the plotter accessory and then are recorded on data files for

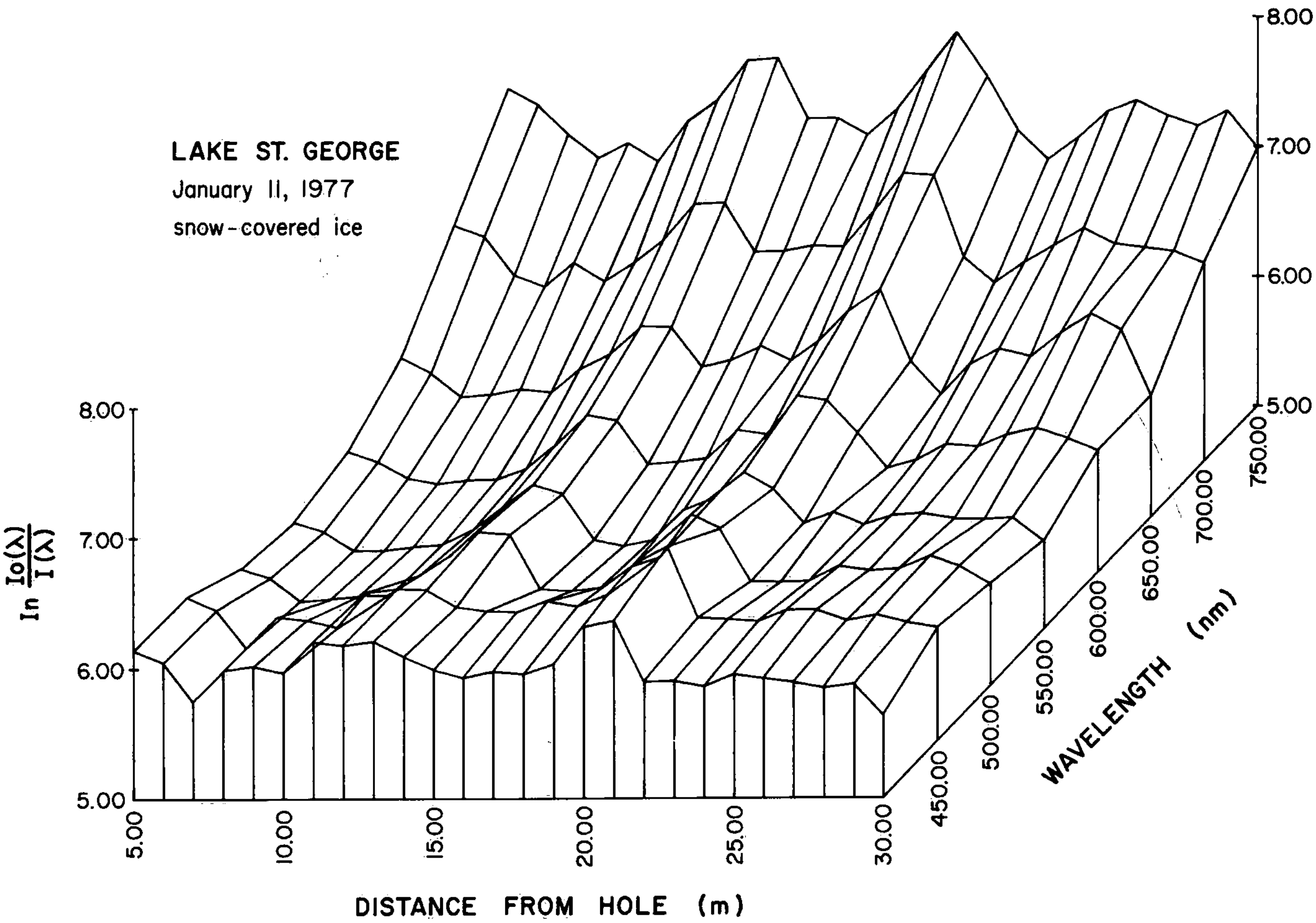

Figure 17. Irradiance results obtained at Lake St. George, Ontario, January 11, 1977, with under ice sled and QSM 2500 in a three-dimensional plot after processing data with a Hewlett-Packard 9830.

processing. Calibration factors for instrument response and wavelength are then applied; various graphical or tabular presentations of the data are available using programs written in Hewlett-Packard BASIC. A typical plot is presented in Figure 17, which represents the downwelling irradiance below ice at Lake St. George, Ontario, in terms of a surface over wavelength and distance horizontally under the ice.

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