Ferdinand J. Bonn
Université de Sherbrooke
Sherbrooke, Québec J1K 2R1, Canada

Ground Truth Measurements for Thermal Infrared Remote Sensing

Seasonal variations of regression coefficients between soil surface temperatures and remotely sensed thermal radiation are higher on vegetated areas than on bare soil.

Abstract: *Since 1971, field measurements have been made in order to establish interpretation keys for remotely sensed thermal infrared radiation in the 9.5 to 11.5 micrometer spectral range. The infrared radiation emitted by different land surfaces has been measured with a Barnes PRT5 radiometer and compared with different environmental parameters (solar radiation, net radiation, air and soil temperature at various depths, air and soil moisture, etc.). The parameters that give the closest correlation with the remotely sensed thermal radiation vary with the type of vegetable cover and with the seasons. The best correlations are obtained with soil surface temperature over bare soil and with air temperature at half the canopy height over vegetated areas. Seasonal variations of regression coefficients between soil surface temperatures and remotely sensed thermal radiation are higher on vegetated areas than on bare soil.*

Introduction

In conventional air photo interpretation, and in remote sensing methods devoted to the identification of terrestrial targets, the term "ground truth" is generally used for a verification made in the field to test the validity of the photo interpreter's deductions, and to correct the interpretation if possible.

Thermal infrared imagery generally is used to obtain information concerning the radiance, and thus the temperature, of ground surfaces. Repetitive thermal infrared measurements over the same surfaces should then give information on differences in the heating and cooling characteristics of these surfaces. These characteristics may lead to determinations of the terrain's thermal parameters. The most frequently used thermal parameters for soils are given in Table 1.

If the assumption is made that the soil is homogenous and isotropic, the temperature distribution in soils generally is given by the heat-flow equation (Rose, 1966)

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial Z^2} \qquad (1)$$

where T is the temperature, t the time, Z the depth, and a the thermal diffusivity as shown in Table 1.

The heat capacity per unit volume of soil is related to soil moisture variations, and can be calculated within 5 percent for most soils, using a formula by de Vries (1952):

$$\rho C = 0.46\ \theta_m + 0.6\ \theta_o + \theta_w \qquad (2)$$

where θ_m, θ_o, and θ_w, are volume fractions of mineral material, organic matter, and water respectively. It is to be noted that:

Photogrammetric Engineering and Remote Sensing,
Vol. 43, No. 8, August 1977, pp. 1001-1007.

$$\theta_m + \theta_o + \theta_a + \theta_w = 1 \tag{3}$$

where θ_a, volume fraction of air, has little influence on ρC, because air has a volumetric heat capacity of only 0.00029, but an important one on the conductivity, k, due to the low conductivity of air (0.00006) compared to water (0.0014). An increase of water content will then, according to Rider (1957), increase the conductivity by filling air spaces.

The thermal inertia, P, as a consequence, will vary according to the moisture content. Since it is now possible to map thermal inertia from remote sensing data (Kahle *et al.*, 1975), thermal infrared scanning of the earth surface should be a good soil moisture mapping tool, if the remote sensors really detect the soil surface.

One of the purposes of the study made in Sherbrooke is to compare contact and noncontact (remotely sensed) temperature data, and to find out which thermal parameter correlates closest with the remotely sensed radiance temperature and could be used as a ground truth reference for further surveys.

Methodology

The study has been carried out on five experimental plots located in the Physical Geography Experimental Basin on the university campus at Sherbrooke, Québec. All five plots are on slopes ranging from 8° to 15°, facing southwest. Surficial deposit is a silty glacial till, approximately 1 meter thick, underlayed by preordovician shales. Glacial till covers approximately 60 percent of the Sherbrooke area. The plots differ one from another by their vegetal cover: one is maintained on bare soil, one is grass covered, one is under a pine canopy with regular removal of the pine needles falling on the ground, another is under the same canopy but without removal of the needles, and the last is located on the steepest slope with only a thin (30 cm) layer of till, and is covered with grass and small bushes. The plots are equipped as erosion plots, and serve at the same time as test surfaces for remote sensors. A complete description of the test area has been published (F. Bonn and P. Clément, 1974).

Measurements are continuing and since 1971 have been done with remote sensing equipment. Different types of measurements have been made at different time intervals. Many results have been obtained from intensive measurement periods approximately one week long in which temperature and radiation measurements were taken at short time intervals (two hours or less), day and night. Table 2 summarizes the measurements taken during these intensive measurement periods, the results of which are presented here.

In addition to these intensive measurements, daily measurements of temperature and radiation are taken all year around at solar noon. Since 1975 an Exotech model 100 ERTS Ground truth radiometer has been used to give information on the reflected energy in the four Landsat spectral bands.

Results

The results presented here concern mainly the bare ground and the grass covered plot because different thermometer locations are still being tested on the forested plots.

Figure 1 shows an example of differences in Thermal IR emitted by different surfaces. At this time of the year (June) around noon, the following succession from "warm" to "cold" is typical: Bareground, grassland, coniferous, deciduous. The same succession has been observed in June from flights made at 300 meters altitude over the same area using a small aircraft and an 8-14 μm Barnes PRT5 (Lajeunesse, 1974).

At night, especially at pre-dawn measurements, thermal inertia models would lead us to expect a reversal of the noon values. This

Table 1. Thermal Parameters Used in Soil Thermal Studies

Parameter	Symbol	Description	Units
Thermal conductivity	k	Quantity of heat flowing through a 1 cm thick layer during 1 second when there is a 1°C temperature difference.	cal $cm^{-1}s^{-1}$ $°C^{-1}$
Specific heat	C	Quantity of heat necessary to raise the temperature of 1 g by 1°C.	Cal g^{-1} $°C^{-1}$
Density	ρ	Weight-per-volume unit	g cm^{-3}
Volume heat capacity	ρC	Quantity of heat necessary to raise the temperature of 1 cm^3 by 1°C.	cal cm^{-3} $°C^{-1}$
Thermal diffusivity	a	$a = k/\rho C$	cm^2 sec^{-1}
Thermal inertia	P	$P = \sqrt{k\rho C} = \rho C\sqrt{a}$	cal $cm^{-2}s^{-1/2}°C^{-1}$

TABLE 2. ENVIRONMENTAL PARAMETERS, TECHNIQUES, AND INTENSIVE MEASUREMENT PERIODS

Measurement periods		1971			1972					1973			
Parameters	Techniques	May 11th–15th	July 9th–13th	Sept. 29th –Oct. 2nd	May 17th–23rd	July 9th–14th	July 31st –Aug. 5th	Aug. 27th –Sept. 1st	November 13th–18th	May 16th–25th	June 18th–23rd	July 22nd–27th	August 20th–25th
Incoming solar radiation	Mechanical pyranograph	X	X	X	X	X	X	X	X	X	X	X	X
Outgoing terrestrial radiation	Barnes PRT5 9.5-11.5 μm	X	X	X	X	X	X	X	X	X	X	X	X
Outgoing terrestrial radiation	Barnes PRT10 7-14 μm										X	X	X
Air temperature and moisture	Standard shelter & psychrometer	X	X	X	X	X	X	X	X	X	X	X	X
Air temperature at 30 cm above soil	Thermistor probe							X	X	X	X	X	X
Soil surface temperature	Thermistor probe	X	X	X	X	X	X	X	X	X	X	X	X
Soil temperature at 5, 10, 20, 30 cm depth	Thermistor probe	X	X	X	X	X	X	X	X	X	X	X	X
Soil moisture	Bouyoucos gypsum blocks	X	X	X	X	X	X	X	X	X	X	X	X
Soil water suction	Tensiometers							X		X	X	X	X
Net radiation	S.R.I. Net radiometer											X	X
Soil heat flux	S.R.I. Flux plates											X	X

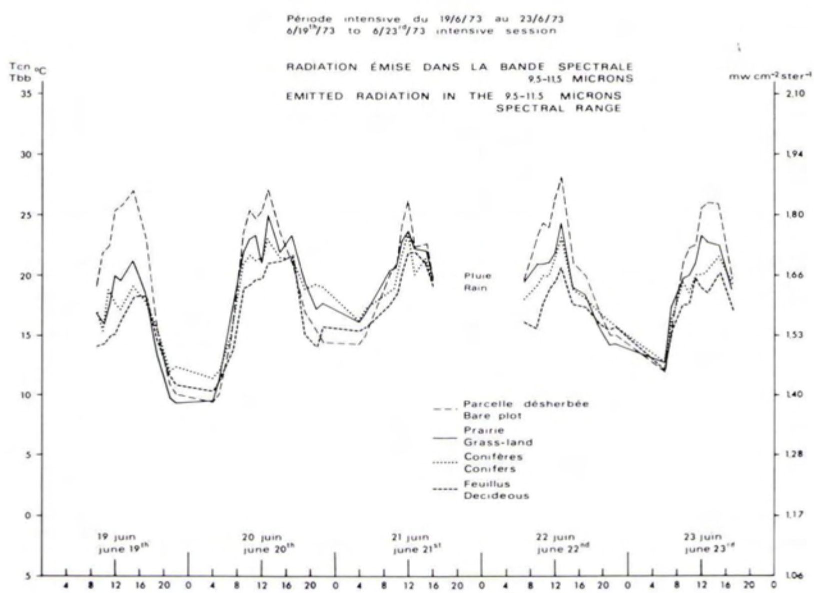

FIG. 1. Thermal infrared emissions from different surfaces in June.

does not occur, however, and there is no simple explanation for it. The soil-plant system is a non-homogenous media through which different air flows can take place. These flows can be downhill cold air during inversions on clear nights, such as the night from 19th to 20th, or southwest warm winds going uphill, such as the night from 20th to 21st.

Figure 2 shows a different type of succession in May. By this time of the year, in our area, the grass cover has not yet started its biological activity such as evapotranspiration, and appears then as a dry strawmat having lower thermal inertia than the bare soil, still wet from snowmelt. The expected crossover at night does not always occur, as on the night from 19th to 20th. Some dew condensation was observed on the grass that night.

Figure 3 shows the same plots in fall. Their noon emissions are not significantly different.

The seasonal succession at noon from spring, when the grass covered plot appears "warmer," through the summer, when the bare ground emits the most and on to autumn, when there is no significant difference at noon, has been the same since we started the measurements in 1971.

In order to discover which environmental parameter correlates closest with the emitted thermal IR radiation on both plots, correlation coefficients and regression equations have been calculated for each measurement period between the remotely sensed radiation temperature and some temperatures measured directly with thermistor probes.

The first parameter is the air temperature (T_A) measured in the standard meteorological shelter located within 10 meters of the plots. The results are given in Table 3. We did not expect very high correlations, but standard data are the most easily available anywhere. The results show however, that the air temperature, as available from meteorological shelters, is not good ground truth data for thermal infrared remote sensing.

Correlations with radiation temperatures proved to be better, with a mean of 0.92, if the ground truth reference is the surface temperature rather than the air temperature, especially on the bare ground plot. The results are given in Table 4. An example of the regression lines obtained is shown in Figure 4.

Mean correlation coefficients are 0.84 on the grass-covered plot and 0.92 on the bare ground plot. If we do not consider the November 1972 results where the conditions were very particular (partially frozen soil), we obtain means of 0.86 and 0.94 respectively. Regression coefficients vary more on the grass-covered plot (mean: 1.35; standard deviation: 0.38) than on the bare ground (mean: 1.06; standard deviation: 0.14).

This shows that (a) surface temperature variations on the grass-covered plot are smaller than air temperature variations, which is shown by a high mean regression coefficient (1.55), higher than the one obtained when considering air temperature (1.18); and (b) variations from one period to another are higher on the grass-covered plot, as shown

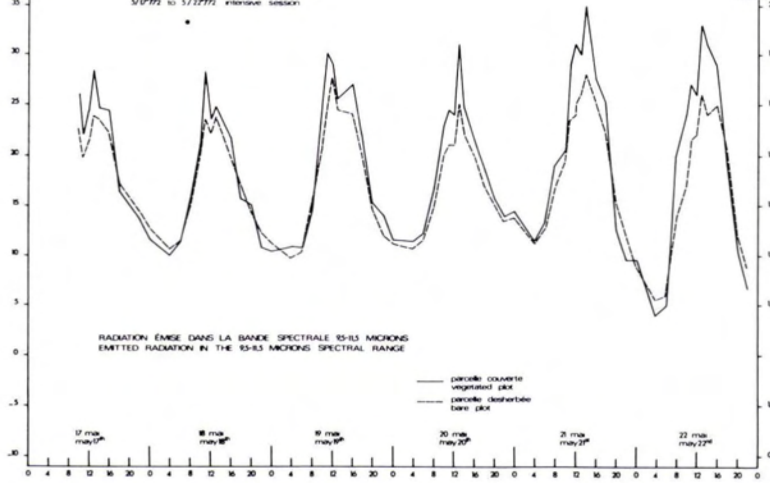

FIG. 2. Thermal infrared emission from two plots in May.

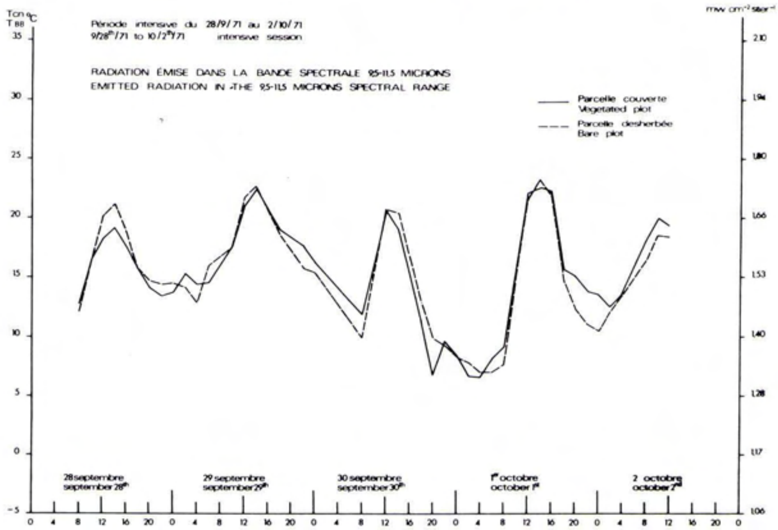

FIG. 3. Thermal infrared emission from two plots in September and October.

by the standard deviations. The two plots being located side-by-side, with only 1 meter of grass between them, we may suppose that micrometeorological conditions are identical. The variations then probably are related to changes in the vegetal activity with the seasons. Therefore, a thermometer located on the soil surface can be considered as a good ground truth reference for bare soil areas on glacial till.

In order to determine a better correlation on the grass-covered surface, we located a thermistor probe 30 cm above the soil surface, this location measuring the air temperature at two-thirds the height of the canopy (T_{AI}). The results are given in Table 5.

The correlation coefficients (mean 0.94) are much better with this thermometer location than with the ambiant air (0.87) or with the surface (0.81) and come close to those obtained with surface temperature on bare ground (0.96 for the same periods). A thermometer located above the soil surface, at two-thirds the canopy height may then be a good ground truth reference for thermal infrared remotely sensed radiance temperatures.

CONCLUSIONS

The following preliminary conclusions may be drawn:

(1) Remote sensing operations of terrestrial

TABLE 3. CORRELATIONS BETWEEN RADIATION TEMPERATURES (T_{BB}) AND AIR TEMPERATURE (T_A)
$T_{BB} = a + b\,T_A$ T_{BB} AND T_A IN °K

Period	Grass-covered plot			Bare plot		
	a	b	r	a	b	r
May 1971	− 3	1.01	0.88	42	0.85	0.89
May 1972	−202	1.70	0.84	− 76	1.26	0.90
May 1973	− 82	1.28	0.85	− 78	1.27	0.88
June 1973	0.51	0.99	0.88	− 17	1.05	0.90
July 1971	− 44	1.15	0.89	−145	1.51	0.82
July 1972	− 42	1.14	0.92	− 66	1.22	0.93
July 1973	−159	1.50	0.87	−161	1.57	0.88
August 1972	− 24.5	1.08	0.89	− 14.7	1.05	0.92
August 1973	− 47	1.15	0.88	− 78	1.26	0.85
Sept. 1971	− 18	1.06	0.88	− 0.4	1.0	0.89
Sept. 1972	− 77	1.27	0.93	−107	1.36	0.95
Nov. 1972	11.5	0.94	0.73	42	0.83	0.77
Mean		1.18	0.87		1.18	0.88

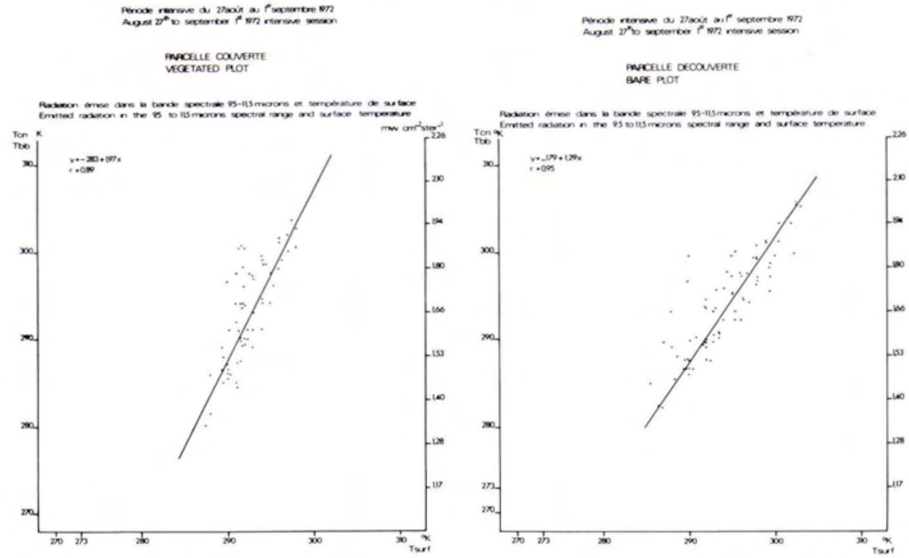

FIG. 4. A sample of regression between soil surface temperatures and thermal infrared radiation remotely sensed in the 9.5 to 11.5 μm spectral range.

surfaces in the thermal infrared area always should be made simultaneously with ground truth measurements if quantitative interpretation of surface thermal parameters is desired because it is impossible to consider blackbody temperatures as true temperatures;

(2) thermal data from traditional meteorological stations are not sufficient to be considered reliable surface indicators, because there is no direct correlation between emitted radiation and air temperature;

(3) on bare-ground surfaces, the best correlations are obtained with a thermometer located on the soil surface;

(4) on grass-covered surfaces, the best ground truth is obtained with a thermometer located at 20-30 cm from the soil surface, at two-thirds the canopy height;

(5) regression coefficients between emitted radiation and surface temperatures are stable and close to 1 on bare soil, but vary with the seasons on vegetated surfaces; and

(6) absolute differences between remotely sensed blackbody temperatures and surface temperatures vary with the time of day and with the season, and these variations are greater on vegetated areas than on bare soil.

TABLE 4. CORRELATIONS BETWEEN RADIATION TEMPERATURES (T_{BB}) AND SURFACE TEMPERATURES (T_S) $T_{BB} = a + b\,T_S$ T_{BB} AND T_S IN °K

Period	Grass-covered plot			Bare plot		
	a	b	r	a	b	r
May 1971	−150	2.42	0.86	− 79	1.27	0.92
May 1972	−173	1.62	0.91	− 34	1.12	0.94
May 1973	−186	1.65	0.79	30.4	0.85	0.97
June 1973	−101	1.34	0.82	− 21.2	0.92	0.97
July 1971	− 59	0.78	0.90	− 80	1.27	0.93
July 1972	−157	1.54	0.90	− 1.30	1.00	0.96
July 1973	−189	1.64	0.82	− 78	1.25	0.95
August 1972	−202	1.68	0.84	− 12	1.03	0.92
August 1973	−226	1.78	0.82	− 17	1.05	0.94
Sept. 1971	− 35	1.12	0.94	− 19.6	0.92	0.91
Sept. 1972	−282	1.97	0.89	−179	1.29	0.95
Nov. 1972	− 43	1.13	0.54	42.8	0.83	0.62
Mean		1.55	0.84		1.06	0.92
Standard deviation		0.38			0.14	

TABLE 5. CORRELATIONS BETWEEN RADIATION TEMPERATURES (T_{BB}) AND AIR TEMPERATURES AT 30 CM ABOVE THE SOIL (T_{AI}), FOR THE GRASS-COVERED PLOT
$T_{BB} = a + b\ T_{AI}$, T_{BB} AND T_S IN °K

Period	a	b	r
May 1973	−28.5	1.08	0.92
June 1973	27.6	0.89	0.95
July 1973	27.3	0.82	0.96
August 1973	−18.5	1.05	0.94
Mean			0.94

RECOMMENDATIONS

In order to facilitate the interpretation of thermal infrared data, and in particular those of the HCMM satellite planned by NASA for 1978, we recommend:

(1) that meteorological stations be equipped with thermometers in the soil and at different levels between the soil and the top of vegetal cover, readings to be taken simultaneously with the flights; and

(2) that experimental test studies be made in other areas in order to determine the most suitable environmental parameters to be considered as ground truth, especially in forested areas.

ACKNOWLEDGMENTS

This research has been supported by grants from the National Research Council of Canada, the Defense Research Board of Canada, and the Quebec Department of Education.

REFERENCES

Auding, F., and R. Kanth (1970). Estimation of Sea Surface Temperature from Space, *Remote Sensing of Environment*, 1, pp. 217-220.

Bonn, F., and P. Clément (1972). Utilization of Thermal Infrared Ground Measurements for Determination of Adequate Surveying Periods in Remote Sensing, *8th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, U.S.A., 2-6 October 1972, pp. 709-714.

Bonn, F., and P. Clément (1974). *Les installations expérimentales extérieures de géographie physique sur les terrains de l'Université de Sherbrooke*, Bulletin de Recherche # 14, Département de Géographie, Université de Sherbrooke, 68 p.

Bonn, F. (1975). *Répartition de l'énergie dans le milieu écologique*, Thèse Doctorat 3e cycle, Université Louis Pasteur, Strasbourg, France, 202 p.

Buettner, K.J.K., and C.D. Kern (1965). The Determination of Infrared Emissivities of Terrestrial Surfaces, *Journal of Geophysical Research*, Vol. 70, No. 6.

Clément, P., and P. Gadbois (1971). Comparaison et interprétation des résultats de deux parcelles expérimentales d'érosion (1969-1970) in *Research Methods in Pleistocene Geomorphology*, E. Yatsu and A. Folconer, ed., Guelph, Ontario.

de Vries, D. A. (1952). *The Thermal Conductivity of Granular Materials*, Bulletin de l'Institut International du Froid, Annexe, 1952-1, 115

Hadni, A. (1967). *Elements of Modern Physics Applied to the Study of the Infrared*, Pergamon.

Jalbert, C. (1973). *Compte-rendu d'observations sur les fluctuations de l'humidité disponible du sol*, Mémoire Bacc. *spécialisé*, Département de géographie, Université de Sherbrooke.

Kahle, A. B., A. R. Gillespie, A. F. Goetz, and J. D. Addington (1975). Thermal inertia mapping, *10th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, October 6-10, 1975.

Lajeunesse, M., and B. Bareilhe (1974). *Interprétation de traverses à l'infra-rouge thermique dans le bassin de la rivière Eaton (Québec)*, Communication au 42e Congrès ACFAS, Université Laval, 8 au 10 mai 1974.

Mattson, R. B. (1969). Thermal Pattern in the Landscape Recorded with Infra-Red Technique and Simulated in Model Experiments. *Geografiska Annaler* 51A, # 4.

Platt, R. B., and J. F. Griffiths (1965). *Environmental Measurement and Interpretation*, Reinhold, 235 p.

Pouquet, J. (1969). Géomorphologie et ère spatiale, *Zeitschrift für Geomorphologie*, 13, # 4, pp. 414-471.

Pouquet, J. (1971). *Les sciences de la terre à l'heure des satellites*, Coll. SUP, PUF, 259 p.

Pouquet, J. (1972). Résultats obtenus avec un radiomètre opérant dans la bande spectrale 10,5-12,5 microns, *Revue de Géomorphologie Dynamique*, XXI, 1.

Rider, N. E. (1957). A note on the physics of soil temperature, *Weather*, 12, 241.

Rose, C. W. (1966). *Agricultural Physics*, Pergamon, 230 p.

Tricart, J., and A. Husson (été 1972). Quelques apports des enregistrements infra-rouges à la connaissance du milieu physicopgéographique, *Annales de Géographie*.

Fall Convention Preliminary Program, pages 1077-1084