NOTA 1057 februari 1978

Instituut voor Cultuurtechniek en Waterhuishouding
Wageningen

ESTIMATION OF THE REGIONAL EVAPOTRANSPIRATION FROM REMOTELY SENSED CROP SURFACE TEMPERATURES

PART II: ARABLE LAND

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CONTENT

I. LIST OF USED SYMBOLS

Symbol	Description	Units
A	total leaf area index	-
A_e	effective leaf area index	-
b	root parameter	m^{-1}
c_p	specific heat per unit mass of air	$J.kg^{-1}.K^{-1}$
d	zero plane displacement	m
D	thichness of the fully adjusted boundary layer	m
E	evapotranspiration flux	$kg.m^{-2}.s^{-1}$
e_a	actual water vapour pressure in the air	Pa
e^*_a	saturated water vapour pressure in the air	Pa
e^*_c	saturated water vapour pressure at temperature T_c	Pa
E_d	total day light evapotranspiration	mm
E_{pot}	evapotranspiration at optimal water supply	$kg.m^{-2}.s^{-1}$
f	fetch	m
g	acceleration due to gravity	$m.s^{-2}$
G	heat flux into the soil	$W.m^{-2}$
h	crop height	m
H	sensible heat flux	$W.m^{-2}$
IR	value of band 9 of Daedalus scanner (near infrared, 0.8-0.89 μm)	-
k	Von Karman's constant	-
K	hydraulic conductivity	$m.s^{-1}$
K_s	hydraulic conductivity of saturated soil	$m.s^{-1}$
L	latent heat of vaporization	$J.kg^{-1}$
OR	value of band 6 of Daedalus scanner (orange, 0.6-0.65 μm)	-
p	pressure of the air	Pa
P_1	stability correction for momentum transport	-
P_2	stability correction for heat tranport	-
r_a	turbulent diffusion resistance for momentum transport	$s.m^{-1}$
r_{ah}	turbulent diffusion resistance for heat transport	$s.m^{-1}$

Symbol	Description	Units
r_s	stomatal diffusion resistance for water vapour transport	$s.m^{-1}$
R_{plant}	plant resistance for liquid water transport	s
R_{soil}	soil resistance for liquid water transport	s
R_l	longwave sky radiation flux	$W.m^{-2}$
R_{lc}	longwave crop radiation flux at ε_c	$W.m^{-2}$
R_{lh}	longwave crop radiation flux at $\varepsilon_c=1$	$W.m^{-2}$
R_{lp}	longwave radiation flux from the test plate	$W.m^{-2}$
R_n	net radiation flux	$W.m^{-2}$
R_s	incoming shortwave radiation flux	$W.m^{-2}$
S_c	soil coverage	-
T_a	air temperature at reference level	K
T_c	crop temperature	K
T_r	radiometrically measured surface temperature	K
T_p	temperature of the test plate	K
T_s	temperature of the soil surface	K
U	wind velocity at reference level	$m.s^{-1}$
U_*	friction velocity	$m.s^{-1}$
X	non-dimensional wind velocity gradient	-
Z_a	reference level in the atmosphere	m
Z_o	crop roughness length	m
α_s	reflection coefficient for shortwave radiation	-
γ	psychometric constant	$Pa.K^{-1}$
ε_c	crop emission coefficient	-
ε_p	plate emission coefficient	-
ϕ	angle between direction of observation and position of the sun	-
λ	heat conductivity of the soil	$W.m^{-1}.K^{-1}$
Λ	Monin-Obukhov length	m
ρ	density of moist air	$kg.m^{-3}$
σ	Stephan-Boltzmann constant	$W.m^{-2}.K^{-4}$
τ	momentum flux	$W.m^{-2}$
θ	zenith angle of observation	-
ψ_l	leaf water potential	Pa
ψ_s	soil water potential	Pa

II. INTRODUCTION

The aim of this study is the estimation of evapotranspiration of arable crops using crop surface temperatures. Crop surface temperatures can be measured with infrared radiation thermometers, build in air planes or satellites and therefore opens potential possibilites of estimating evapotranspiration of large areas.

This study is a continuation of the work of SOER (1977) who developed the TERGRA model, that can be used for the estimation of momentary as well as daily evapotranspiration of grassland. The purpose of this study is to examine if this model, with some modifications if necessary, can be used also for arable crops.

The area under investigation is situated in one of the IJssel Lake Polders near Dronten. It is a rather homogeneous area with a soil that has a good supply of water, so that potential evapotranspiration is frequently reached. This means, that measurement of evapotranspiration from crop surface temperature by means of the energy balance equation can be compared with a calculation method of potential evapotranspiration.

At the time of temperature recordings by air plane many crops had incomplete soil coverage. For interpretation of plots with partial soil coverage an empirical relation between temperature and reflectivity has been developed.

III. THEORY

III.1. Energy balance equation and the use of crop surface temperatures

Evapotranspiration can be calculated from the energy balance equation

$$R_n = G + H + L.E \qquad (W.m^{-2}) \qquad (1)$$

where R_n is net radiation flux, G heat flux into the soil, H sensible heat flux, L.E latent heat flux, the energy equivalent of the evapotranspiration flux $E(kg.m^{-2}.s^{-1})$; L is latent heat of vaporization of water per unit mass ($L = 2.45 \times 10^6\ J.kg^{-1}$).

The net radiation flux is the resultant of incoming and outgoing radiation fluxes

$$R_n = (1 - \alpha_s) R_s + \varepsilon_c (R_l - \sigma T_c^4) \qquad (W.m^{-2}) \qquad (2)$$

where R_s is incoming shortwave radiation flux, α_s crop reflection coefficient for shortwave radiation, ε_c crop emission coefficient, R_l longwave sky radiation flux, σ Stephan-Boltzmann constant (σ = $5.67 \times 10^{-8}\ W.m^{-2}.K^{-4}$) and T_c crop surface temperature (K). The net radiation flux is expressed in this way as it may be assumed, that over larger areas both incoming shortwave and longwave radiation fluxes are constant.

The sensible heat flux H can be written as

$$H = \rho c_p \frac{T_c - T_a}{r_{ah}} \qquad (3)$$

where ρ is air density ($kg.m^{-3}$) and c_p specific heat ($J.kg^{-1}.K^{-1}$) of the air, ($T_c - T_a$) the crop-air temperature difference (K) and r_{ah} turbulent diffusion resistance for heat ($s.m^{-1}$). The factor r_{ah} can be calculated from the diffusion resistance for momentum r_a. The latter may be found from the expression for the turbulent diffusion transport of momentum τ ($W.m^{-2}$):

$$\tau = \rho \frac{U - U_c}{r_a} \qquad (4)$$

where U is the wind velocity at the reference height in the atmosphere and U_c the wind velocity at the surface, so it will be assumed that $U_c = 0$. The transport of momentum also can be expressed as

$$\tau = \rho U_*^2 \qquad (5)$$

where U_* is the friction velocity ($m.s^{-1}$) formulated as

$$U_* = \frac{k.U}{\ln\left(\frac{Z_a - d}{Z_o}\right) - P_1} \qquad (6)$$

where k is Von Karman's constant, here taken 0.4, Z_a the height (m) of measurements, d the zero plane displacement (m), Z_o the crop roughness length (m) and P_1 the stability correction for momentum transport. As U_* is independent of height, Z_o can be calculated from eq. (6) by measurement of wind velocity at different heights. After rearranging and differentiating:

$$U = \frac{U_*}{k}\left[\ln\left(\frac{Z_a - d}{Z_o}\right) - P_1\right]$$

so

$$\frac{\partial U}{\partial Z_o} = -\frac{U_* \ln Z_o}{k\,(Z_a - d)} + \frac{U_*}{k}\,\frac{\partial P_1}{\partial Z_a}$$

or

$$\ln Z_o = -k\,\frac{\partial(U/U_* - P_1)}{\partial \ln(Z_a - d)} \qquad (7)$$

The resistance for momentum transport can be calculated from the eqs. (4) to (6):

$$r_a = \frac{\left[\ln\left(\frac{Z_a - d}{Z_o}\right) - P_1\right]^2}{k^2 U} \qquad (8)$$

From this equation the resistance for heat transport can be calculated. Assuming Reynolds analogy (equal exchange coefficients for the exchange of momentum and heat) means that the different atmospheric resistances will be equal. However, it is found, that the stability correction may deviate for the different exchange processes. Then the atmospheric resistance for heat transport can be expressed as:

$$r_{ah} = \frac{\left[\ln\left(\frac{Z_a - d}{Z_o}\right) - P_1\right]\left[\ln\left(\frac{Z_a - d}{Z_o}\right) - P_2\right]}{k^2 U} \qquad (9)$$

where P_2 is the stability correction for heat transport. Eq. (9) may be used for flat surfaces such as bare soils, where the logarithmic wind and temperature profiles may be used until the surface. In a crop canopy, however, the Reynolds analogy is not valid because the sources of momentum and heat transport are generally different situated. Therefore a correction is needed. THOM (1972) suggested:

$$r_{ah} = \frac{\left[\ln\left(\frac{Z_a - d}{Z_o}\right) - P_1\right]\left[\ln\left(\frac{Z_a - d}{Z_o}\right) - P_2\right]}{k^2 U} +$$

$$+ 6.27 \frac{U.k}{\ln\left(\frac{Z_a - d}{Z_o}\right) - P_1} \qquad (10)$$

The stability corrections P_1 and P_2 can be calculated from the Monin-Obukhov length Λ, expressed as

$$\Lambda = \frac{\rho c_p U_*^3 T_a}{kg\, H} \qquad (11)$$

where g is the acceleration due to gravity ($g = 9.81\ m.s^{-2}$). Under unstable conditions ($T_c > T_a$) the following correction is used (PAULSON, 1970)

$$P_1 = 2 \ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2 \text{ arctg } x + \pi/2 \qquad (12)$$

$$P_2 = 2 \ln\left(\frac{1+x^2}{2}\right) \qquad (13)$$

where

$$x = \left(1 - 16 \frac{Z_a - d}{\Lambda}\right)^{0,25} \qquad (14)$$

In stable atmosphere the correction established by WEBB (1970) is used:

$$P_1 = P_2 = 4.7 \frac{Z_a - d}{\Lambda} \quad \text{for } Z_a - d < \Lambda \qquad (15)$$

and

$$P_1 = P_2 = 4.7 \quad \text{for } Z_a - d > \Lambda \qquad (16)$$

The flux of latent heat can now be calculated as a function of crop temperature from the eqs. (1), (2) and (3) and the expression for r_{ah} of eqs. (9-16) giving

$$L.E = \rho c_p \frac{T_a - T_c}{r_{ah}} - G + (1 - \alpha_s) R_s + \varepsilon_c (R_l - \sigma T^4) \quad (17)$$

As flux of latent heat is not a function of crop temperature only, the relationship between L.E and T_c will be different for different crops. Especially differences in r_{ah} may cause large deviations in calculated evapotranspiration, as can be seen in Fig. 1.

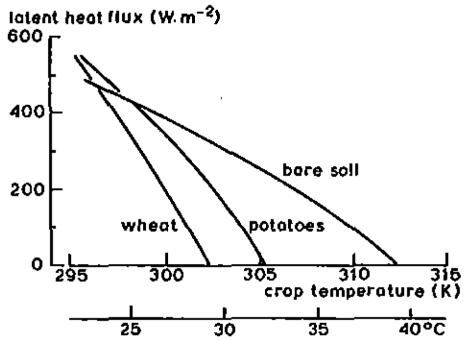

Fig. 1. Evapotranspiration as a function of crop surface temperature T_c for wheat, potatoes and bare soil for the meteorological conditions at June, 14 around flight time (11.48 solar time): $R_s = 761\ W.m^{-2}$, $R_l = 344\ W.m^{-2}$, $G = 40\ W.m^{-2}$ and $U = 3.6\ m.s^{-1}$. The following parameters have been used:

surface type	crop roughness length	reflectivity	emissivity
wheat	0.14 m	0.20	0.98
potatoes	0.05 m	0.18	0.98
bare soil	0.002 m	0.17	0.97

III.2 The TERGRA model

With the aid of the TERGRA model (SOER, 1977b) both sensible and latent heat flux can be simulated. In the model it is assumed, that vertical transport of water is equal in the atmosphere, crop, roots and soil. This implies for steady state conditions and without soil evaporation. This second assumption may be valid only for conditions of nearly full soil cover. Water transport to the leaves can then be expressed as (FEDDES and RIJTEMA, 1972):

$$E = \frac{\psi_l - \psi_s}{g\,(R_{plant} + R_{soil})} \qquad (18)$$

where ψ_l is the water potential in the leaves (Pa), ψ_s is water potential in the soil (Pa), R_{plant} and R_{soil} the flow resistance in the appropiate medium (s). The resistance in the soil can be expressed as

$$R_{soil} = b/\left[K\,(\psi_s)\right] \qquad (19)$$

where b is a root parameter (m) representing the geometry of flow and K (ψ_s) the hydraulic conductivity ($m.s^{-1}$). From eqs. (18) and (19) ψ_s can be calculated as a function of the transpiration and the soil water potential ψ_s. Water transport in the atmosphere can be expressed as

$$L.E = \frac{\rho c_p}{\gamma}\,\frac{e_c^* - e_a}{r_a + r_s} \qquad (20)$$

where γ is psychometric constant (γ = 67 $Pa.K^{-1}$), e_c^* is saturated water vapour pressure (Pa) at the apparent crop temperature T_c, e_a the water vapour pressure (Pa) at reference level in the atmosphere and r_s stomatal resistance of the crop ($s.m^{-1}$). The latter can be written as a function of leaf water potential ψ_l and incoming shortwave or net radiation (R_s or R_n), see Table 1.

Table 1. Stomatal and plant resistances as used in the TERGRA model

Crop	Stomatal resistance, r_s ($s.m^{-1}$)	Plant resistance, R_{plant} (s)
grass	$r_s = 4.52 \times 10^{-12}(-\psi_l)^{2.1} + \frac{400}{R_s + 1.5}$	10^9
potatoes	$r_s = 55 \times 10^{-9}(-\psi_l)^{1.5} + 400 - 1.6 R_s$ ($R_s < 250$) $r_s = 55 \times 10^{-9}(-\psi_l)^{1.5}$ ($R_s > 250$)	0.9×10^9
wheat	$r_s = 10 \exp(-1.27 \times 10^{-6}\psi_l) + \frac{5 \times 10^4}{(R_n + 50) A_e}$	10^9

Values of r_s and R_{plant} for grass are taken from SOER (1977b), potatoes from FEDDES and RIJTEMA (1972) and of wheat from DENMEAD and MILLAR (1977). Values of r_s from DENMEAD and MILLAR are taken per unit of leaf area. Therefore these values must be divided by the effective leaf area index. The effective leaf area index A_e is calculated from the measured total leaf area index A by (MONTEITH, 1973).

$$A_e = 0.5\,A \tag{21}$$

For calculating the latent heat flux with eq. (20) crop temperature should be determined. This can be done by calculating sensible heat flux (with the aid of eq. (3)) and heat flux into the soil. Then all terms of the energy balance equation are known. In the TERGRA model crop temperature is iteratively changed until eq. (1) is satisfied within a certain accuracy, taken as 0.5 $W.m^{-2}$.

III. 3. Crop emissivity

When crop temperature is determined with the aid of a radiation thermometer, the crop emissivity must be known. This is usually not the case. In the following a method as derived by FUCHS and TANNER (1966) will be described by which ε_c can be determined. The method is based on measurement of the longwave reflectivity (= $1-\varepsilon_c$). This is done by changing the amount of incoming radiation. Incoming radiation is changed by putting a longwave radiation reflecting hood on the crop. In that case incoming radiation is equal to outgoing radiation and eq. (2) can be simplified to

$$\varepsilon_c\,(R_l - \sigma T_c^4) = 0 \tag{22}$$

So $R_l = \sigma T_c^4$ and the crop radiation in the hood, R_{lh} (as measured with the radiation thermometer) will be

$$R_{lh} = \sigma T_c^4 \tag{23}$$

This radiation is compared with the longwave radiation R_{lc} as measured without hood

$$R_{lc} = \varepsilon_c \sigma T_c^4 + (1-\varepsilon_c) R_l \tag{24}$$

Taking the difference of eq. (23) and (24):

$$R_{lh} - R_{lc} = (1-\varepsilon_c)\ \sigma T_c^4 - (1-\varepsilon_c) R_l \tag{25}$$

or

$$1-\varepsilon_c = \frac{R_{lh} - R_{lc}}{\sigma T_c^4 - R_l} \tag{25}$$

Longwave radiation of the sky can be determined by measuring the sum of emitted and reflected longwave radiation R_{lp} from a test plate of known temperature and emissivity that is facing the sky.

$$R_{lp} = \varepsilon_p\ \sigma T_p^4 + (1-\varepsilon_p) R_l$$

or

$$R_l = \frac{R_{lp} - \varepsilon_p\ \sigma T_p^4}{1-\varepsilon_p} \tag{26}$$

For a reliable determination of crop emissivity the following requirements must be satisfied:

- The crop temperatures in eqs. (23) and (24) must be the same. Therefore measurements with and without hood must be performed within very short intervals. The experiment must be carried out when shortwave radiation flux is almost zero and wind velocity is low, so that it may be expected that the temperature of the crop will remain practically constant.
- The longwave radiation difference between crop and sky (denominator of eq. (25)) must be sufficiently high. As longwave sky radiation will drop in clear sky, accurate measurements can only be performed under clear sky conditions.

- For a reliable measurement of longwave sky radiation flux, the emissivity of the test plate ε_p (see eq. 26) must be considerably smaller than 1.

As stated before, with this method incoming longwave radiation is changed by putting a hood on the canopy. Another way of changing the received radiation is by using an artificial heat source as proposed by BECKER (1977). In that case there is no need to measure under clear sky conditions. When a fast fluctuating heat source is used, the influence of warming and cooling of the surface can also be diminished, so that determination of crop emissivity will be possible under all kind of circumstances.

III.4. Incomplete soil coverage

In the case of incomplete soil coverage the scanner views partly the canopy and partly the soil. Canopy and soil may be different in temperature. So for temperature interpretation the amount of soil coverage should be known. Soil coverage can be calculated from the surface reflectivity.

All crops show an infrared reflectivity that is larger than the reflectivity of the soil. Mostly the reflectivity in the visible light (especially in the red wavelength band) is smaller for crops than for soil. Therefore, as more soil is covered with a crop the infrared reflectivity (0.8-0.89 μm) will increase and the reflectivity in the orange wavelength band (0.6-0.65 μm) will decrease. By taking the ratio of these reflectivities a measure of soil coverage is found (VERHOEF and BUNNIK, 1975).

In the case of partial soil coverage a relation between the ratio of these reflectivities and the temperature may be expected. Unshaded soil has a high temperature because it shows a small heat exchange. When more crop is present, the scanner will view less warm soil. Also more soil will be shaded and this shaded soil will get a lower temperature.

IV. MATERIALS AND METHODS

The experiments were carried out on an agricultural area in one of the IJssel Lake Polders near Dronten, $17^{o}30'$ east longitude and $50^{o}13'$ north latitude. The soil is a silty clay. The phreatic surface varied between depth of 1.2 m to 1.6 m. Meteorological and soil moisture measurements were performed on a wheat field of 240 x 300 m. The following measurements were taken.

Incoming shortwave radiation was measured with a Kipp CM5 solarimeter, net radiation of the wheat canopy with a SRI4 net radiation meter, positioned at 2 m height. Surface albedo was measured with a SRI solari-albedo meter. Air temperature and wet bulb temperature were determined using copper-constantan thermocouples at 2 m height. Wind velocity was measured at 2 m height with a Thiess 0.315 m ∅ anemometer. Soil heat flux was measured at 4 and 8 cm depth, using perforated SRI heat flux plates. Soil temperature was determined with thermistors placed respectively at the 2, 4, 6, 10, 15, 20, 30 and 40 cm depths. Crop surface temperature was measured with a Heimann K24 radiation thermometer, placed 5 m above the canopy, with a 37^{o} view angle. The instrument was field calibrated, using a tube blackbody radiator of known temperature and emission coefficient.

The output of these instruments was automatically recorded at 3 minute intervals by a TFDL cassette datalogger.

On June, 14 leaf water potential was measured using a pressure bomb from the TFDL. For measurements of the emission coefficient a reflecting hood was build. Sky temperature was measured with an aluminium plate of known emissivity ($\varepsilon_p = 0.96$) from which the temperature could be measured with thermocouples.

For measurement of the leaf area index the surface of the leaves and stems was determined by putting them on a light passing tray.

Soil cover was photographed with a film sensitive to near infrared radiation. All living plants show a high reflectance for infrared radiation. Therefore plants could be easily distinguished from soil (Fig. 2). The images were processed with the aid of the Quantimet 700. Spectral characteristics of some canopies were measured. On May, 17

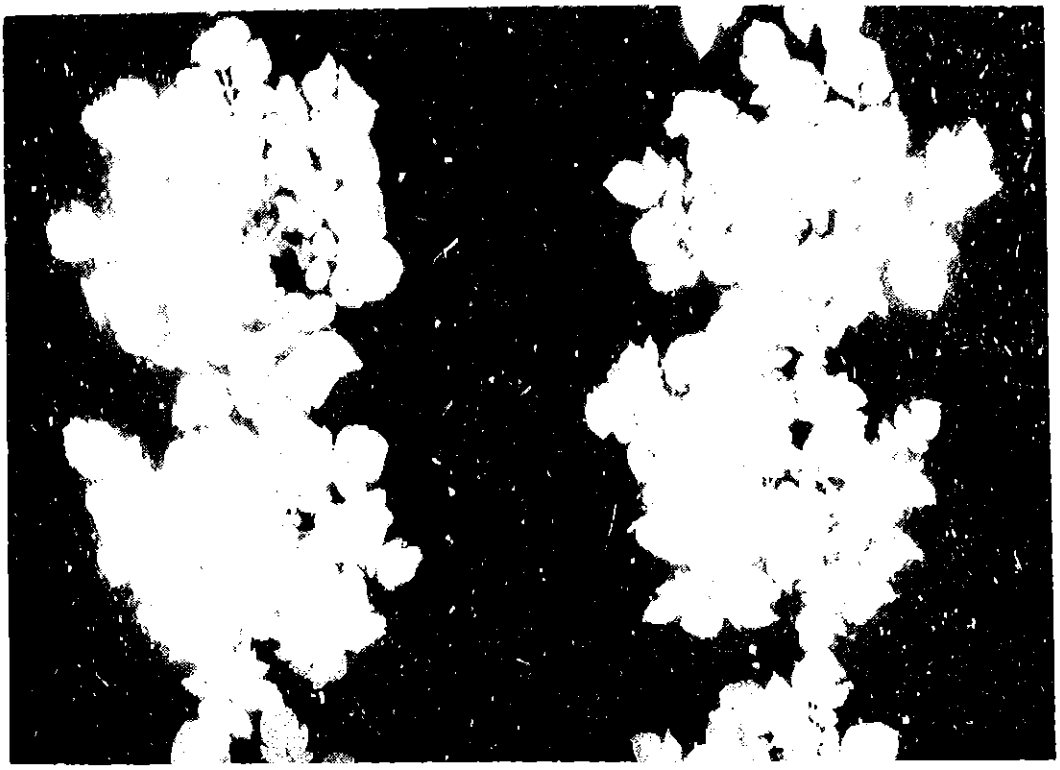

Fig. 2. Infrared photograph of a field plot grown with potatoes with a soil coverage of 0.56 ± 0.05 as photographed from a position at 2 m height perpendicular to the earth.

and August, 8 the measurements were taken with the aid of the EXOTECH spectrometer, by which the reflectivity is registrated in 4 spectral bands: o.5 - 0.6 µm, 0.6 - 0.7 µm, 0.7 - 0.8 µm and 0.8 - 1.0 µm. On June, 9 the NIWARS spectrometer was used, providing spectral reflectances of about seventy separate wavelength bands in the 0.36 - 2.4 µm region.

Soil water potential was measured by tensiometers at 0.2, 0.4, 0.7, 1.0 and 1.3 m depths. Soil water content was measured in 10 cm depth intervals down to 1.3 m with the aid of the γ-transmission method. Depth of the phreatic surface was measured in plastic pipes, that were perforated and wrapped in nylon filter cloth at the bottom ends. Rainfall was recorded with a KNMI rainfall recorder with a surface area of 0.04 m^2 placed at crop height. The relation between hydraulic conductivity and water potential for this soil was measured for different soil depths in the laboratory using the instantaneous profile method.

Two IRLS recordings of the study area were taken in 1977. Both recordings - on May, 17 and June, 14 - were on clear days after a relatively wet period. The air borne recordings were taken with a Daedalus multiband scanner, provided with 10 reflectivity bands in the 0.38 - 1.1 μm region and a thermal infrared radiation band of 8 - 14 μm. The instrument scans the earth surface by means of a rotating mirror in scanlines perpendicular to the flight direction. In one scanline radiation from the earth surface is recorded 674 times. Each separately, integrally scanned surface element is called a pixel. In this recordings the dimension of a pixel is about 2.8 x 3.0 m. Thermal radiation was calibrated on a 'cold' and a 'hot' blackbody inside the scanner unit, which temperatures can be adapted to the variety of surface temperatures to be expected. For the May, 15 recording, blackbody temperatures were set equal to 8 and 44^{o} C, for June, 14 at 16 and 40^{o} C. The information received was converted to digital numbers and recorded on magnetic tape.

Around flight time a number of ground truth data were collected. Crop species, crop height, soil cover and general state of crop and soil were recorded.

V. IMAGE INTERPRETATION

V.1. Recording at May, 15

A print of the recording of the thermal band is seen in Fig. 3. Temperatures ranged between 15^{o} C (black) and 30^{o} C (white). At the time of the recording the air temperature was 15^{o} C. On the map (Fig. 4) the behaviour of the different corps is seen. Canopies like winter wheat and rape-seed which already had obtained a considerable soil coverage show a lower temperature. Reason for this lower temperature is the large crop roughness of tall canopies. Because of the large crop roughness crop temperature will have about the same value as the air temperature. Other crops, for instance summer grains with a soil coverage of 10 - 20 per cent, can hardly be distinguished from bare soil. Plots with potatoes, sugarbeets and oniums have a soil coverage of less than 2% and

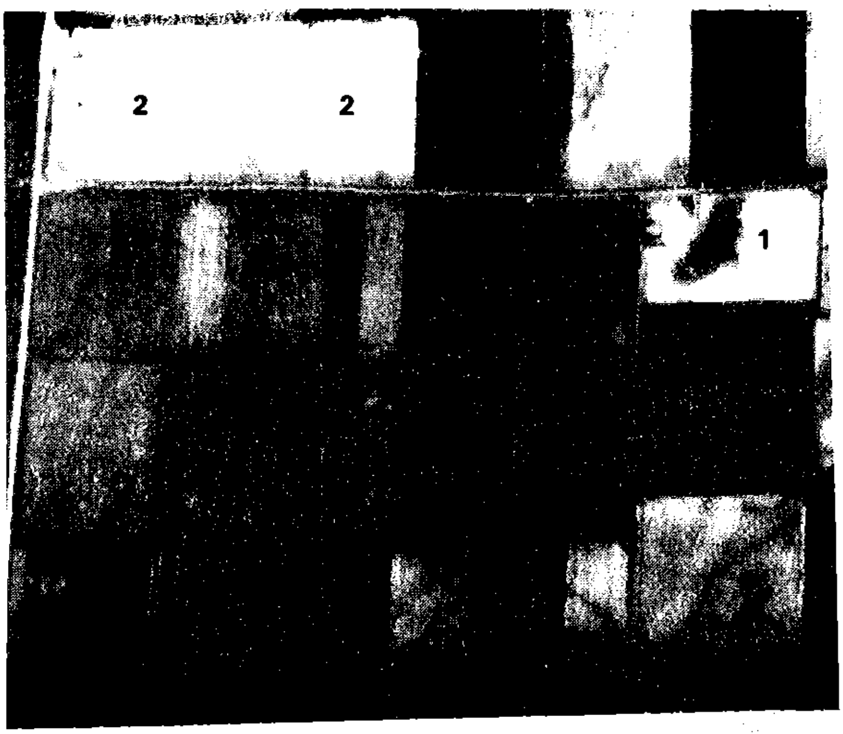

Fig. 3. Positive print of part of the test area near Dronten in the thermal band (8-14 μm) of the Daedalus scanner for May, 15

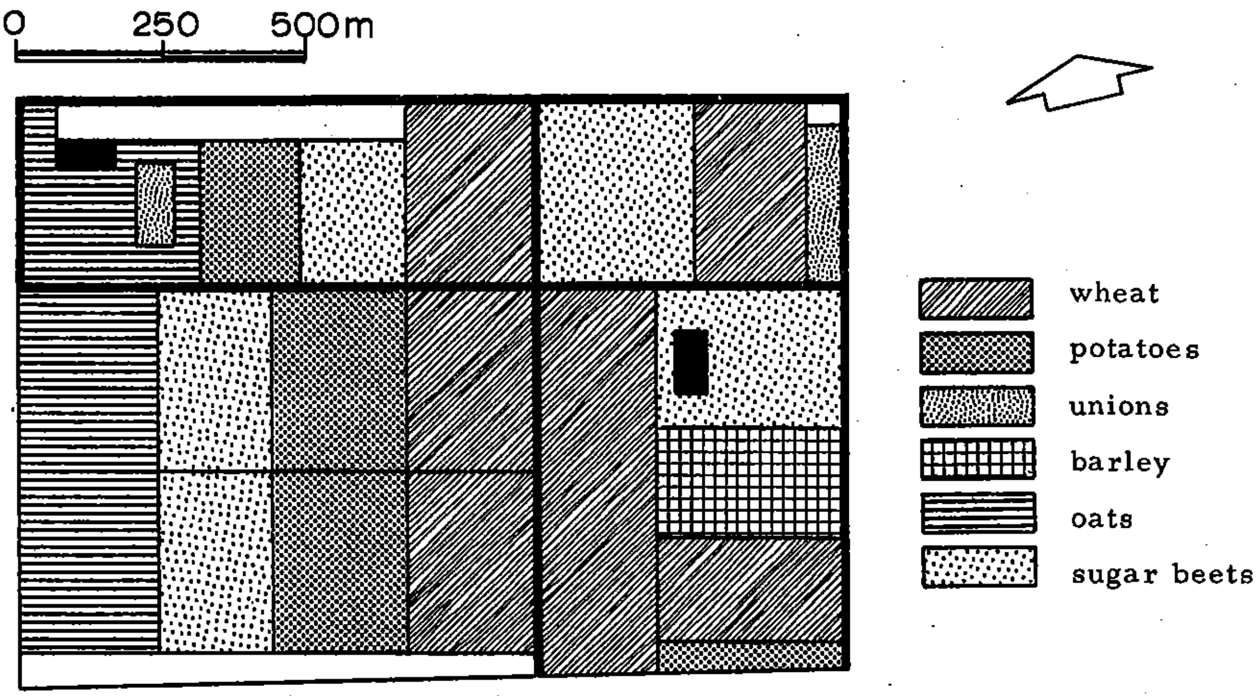

Fig. 4. Map of the various crop types that were found in part of the test area denoted in Fig. 3.

therefore still act as bare soil. Because of rainfall during previous days only a few soils were dry. When the surface layer of the soil gets dry, evaporation gets reduced and a high temperature occurs. In the field marked 1 in Fig. 3 a temperature difference of about 10 K was measured. This is because the inner part of the field has 10% 10% more clay (particles $< 2\ \mu m$), than its surroundings, so that the upper layer of the soil is here relatively wet. The high temperature of the fields marked 2 in Fig. 3 is probably because of different tillage operations. The fields were already shoveled, so that the soil gets looser and the upper layer dries faster. So from the temperature image a good qualitative impression of the transpiration of planted soil and of the moisture condition of bare soil can be obtained.

V.2. Recording at June, 14

This flight was taken after some clear days, so that the upper layer of the soil was dry. All winter and summer grains showed almost full soil coverage (> 80%) and a temperature that differed only a little from the air temperature. Potatoes and sugarbeets had a soil coverage of about 50%.

Flight direction was almost perpendicular to the sun. In Fig. 5

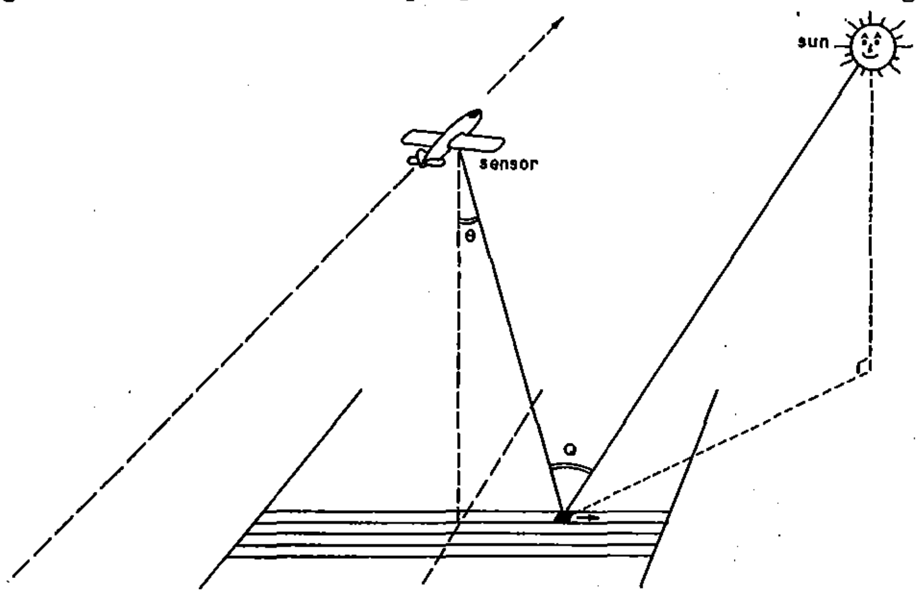

Fig. 5. Surface scanning with an airborne remote sensor, indicating the observation angle to the earth, θ, and the angle between observation and incoming radiation, ϕ. On a scanline both angles will change, resulting in a change of penetrability of radiation in the canopy and the amount of observed shade respectively.

it can be seen that this fligt direction causes large variations in the angle ϕ between the direction of observation and direction of the sun. Reflectance of the canopy may depend on the angle ϕ as a relatively large amount of shade will be present in the pi·ture for large values of ϕ. In Fig. 6 the relative reflectance is shown as a function of the angle of observation. Differences in the lapse of

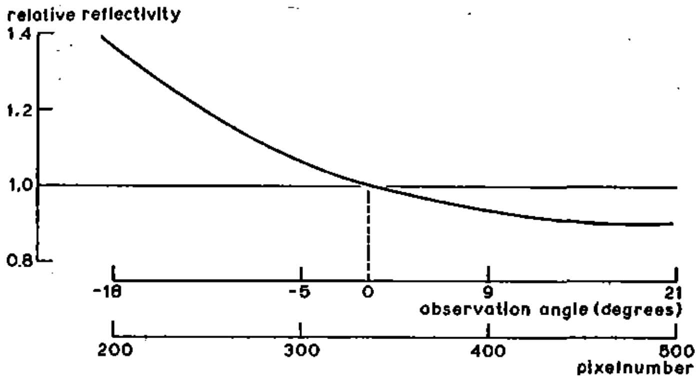

Fig. 6. Corrected reflectance as a function of the angle of observation θ on June, 14. All absolute reflectances were divided by the reflectance that was measured by observation in a direction perpendicular to the earth

reflectance for different crops or for different reflectance wavelength bands were within the accuricy of measurement.

Temperature of a shaded surface element will generally be lower than temperature of an unshaded surface element. Therefore crop temperature may depend on the amount of viewed shading. The temperature observed versus the angle of observation is shown in Fig. 7. In all further calculations crop temperature is corrected for the angle of observation, θ.

The relation between temperature and the ratio of reflectivities orange over infrared is shown in Fig. 8. From this graph it seems that the dependence of temperature on type of crop is small, as the potatoes, sugar beets and some other fields with partial soil coverage are situated around the same regression line. The fields with full soil coverage are also plotted in Fig. 8. It can be seen that these fields show only a small mutual variation.

The encircled point in Fig. 8 represents a field of potatoes, that was irrigated the day befor the flight. Because of this irrigation evapotranspiration increases and a low surface temperature occurs.

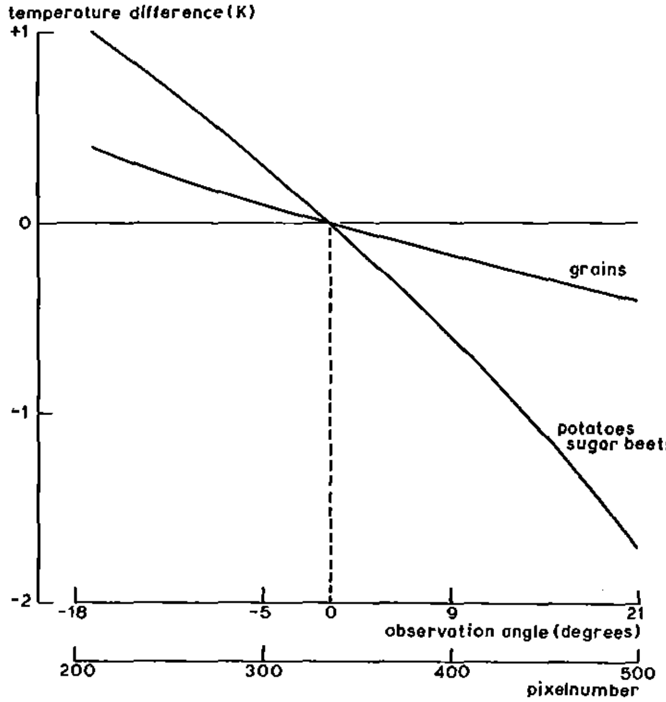

Fig. 7. Observed temperature as a function of the angle of observation θ for June, 14. The temperature that was found by observation in a direction perpendicular to the earth was subtracted from the observed temperature.

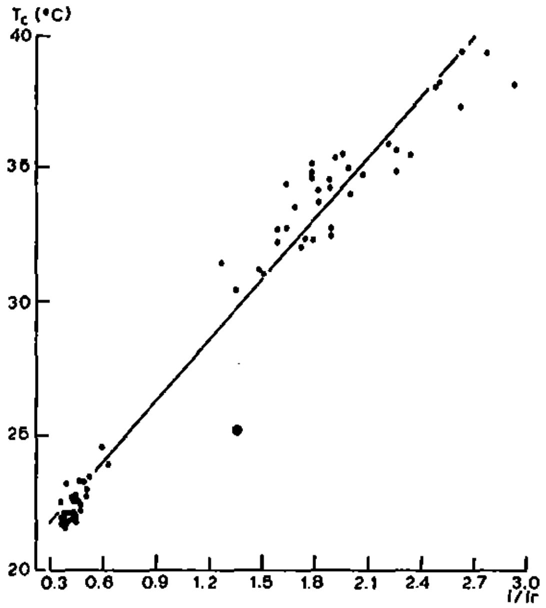

Fig. 8. Temperature as a function of the ratio orange (0.6 - 0.65 μm)/ infrared (0.8 - 0.89 μm) for June, 14

While in the test area all crops had a good supply of water, it is believed that in this case the lower temperature is mainly caused by increased soil evaporation (see also section VI.4).

From Fig. 8 it seems that in this way a good qualitative interpretation of the moisture status can be found. For a more quantitative analysis the use of a TERGRA kind of model is necessary.

VI. RESULTS

VI.1. Crop roughness length

The crop roughness length Z_o of the wheat canopy was indirectly determined by measuring the wind profile above the canopy on July, 11 and 14, 1977 and applying eq. (17). The anemometers were place at heights of 1.5, 1.9, 2.4 and 3.0 m above the ground. Crop height was 1.1 m. Only those measurements were elaborated, which were taken under neutral or near neutral conditions ($|\Lambda| > 50$ m). One typical result is shown in Fig. 9. It is seen, that only the lowest two

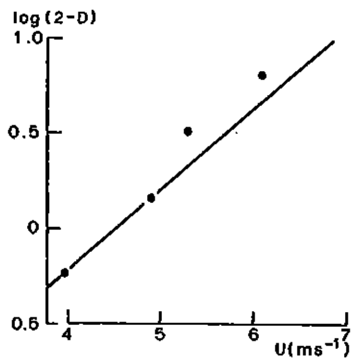

Fig. 9. Horizontal wind velocity profile measured above a wheat crop at June, 20 at 14.10 solar time

anemometers were situated in the fully adjusted boundary layer. This is in agreement with the commonly used rule D = 0.01 f, where D represents the thichness of the fully adjusted boundary layer (m) and f the fetch (m).

As for the calculation only the lowest two anemometers could be used, it was not possible to calculate both Z_o and d. Therefore the value of d was taken from literature: d = 0.64 h (COWAN, 1968). With this value, the crop roughness length was estimated as

$$Z_o = 0.12 \pm 0.04 \quad (m) \tag{27}$$

This is in good agreement with the value, used by Monteith

$$Z_o = 0.13\ h \tag{28}$$

Hence, for all calculations the value of Monteith was accepted.

VI.2. Emission coefficient

Emission coefficients of a number of crops were measured at August, 29 at twilight with clear sky following the method of FUCHS and TANNER (1966). Sky temperature, measured with the radiation thermometer was about 255 K. Due to the high emissivity of the test plate (ε_p = 0.96), sky temperature was more accurately measurable by taking the average of incoming radiation originating from different directions. The temperature difference of the various crops, as measured with and without hood was 0.3 ± 0.2 K. This means that the determination of ($1 - \varepsilon_c$) is not very accurate. The main results are presented in Table 2.

Table 2. Emission coefficients of various crops and soils

Crop	Emission coefficient
mature wheat	0.992 ± 0.010
potatoes	0.991 ± 0.008
moist grass	0.988 ± 0.008
bare soil, dry	0.966 ± 0.008
bare soil, wet	0.974 ± 0.010

The results of Table 2 are in good agreement with measurements of BARTHOLIC et al. (1977), who found for moist soil ε = 0.97 and for dry soil ε = 0.96.

As the crop properties at August, 29 were obviously different from those at June, 14 (soil cover, ripening stage, etc.), it is difficult to use these data for the calculations of June, 14. As no information about sky radiation at June, 14 is available, temperature correction for crop emissivity could not be estimated accurately. In the calculations a correction of -0.5 K was used.

VI. 3. Evapotranspiration

Evapotranspiration of wheat and potatoes was estimated with the aid of the TERGRA model with the meteorological data of June, 14. An example of the result is shown in Fig. 10. Net radiation and ground

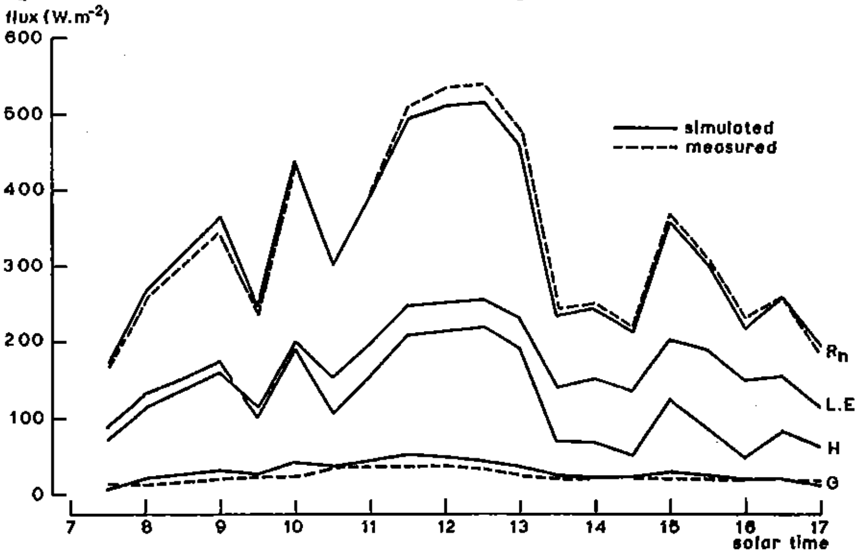

Fig. 10. Net radiation, latent heat flux, sensible heat flux and ground heat flux as simulated with the TERGRA model

heat flux are simulated within the accuracy of measurement. As no data of sensible or latent heat flux were available the accuracy of the simulation of these fluxes is not known.

In order to find the dependence of the model for some parameters, the latent heat flux was integrated over a period of 12 hours. This integrated flux will be called daylight evapotranspiration E_d and will be expressed in mm.

First the dependence of E_d on soil water potential was estimated (Fig. 11). In the calculations, the crop parameters of Table 1 and the soil parameters of Table 3 were used. The soil physical parameters were derived from the relation between soil water content

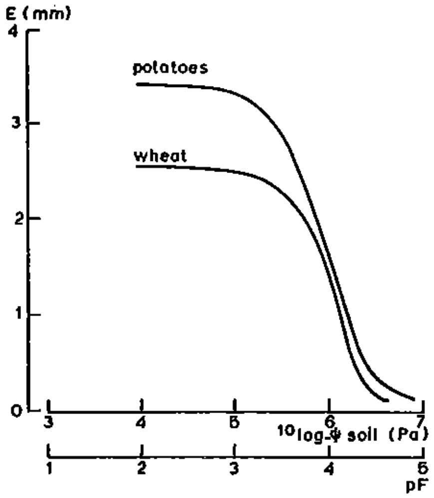

Fig. 11. Daylight evapotranspiration of June, 14 as a function of the soil water potential simulated with the TERGRA model

Table 3. Soil parameters in the test area

Saturated conductivity ($\psi_s > \psi_a$)	K_s=10 cm.day^{-1}(=1.2x10^{-6}m.s^{-1})
Unsaturated conductivity ($\psi_a > \psi_s > -6.10^{-4}$Pa)	$K=K_s\ (\psi_a/\psi_s)^{1.5}$
Unsaturated conductivity ($\psi_s < -6.10^{-4}$ Pa)	$K=K_s\ (\psi_a/-6.10^{-4})^{1.5}$. $.(-G.10^4/\psi_s)^{2.4}$
Air entry value	$\psi_a = 10^3$ Pa
Root density factor	b = 1.3 m (wheat)
	b = 2.6 m (potatoes)

and soil water potential according to BROOKS and COREY (1964).

Fig. 10 shows that potential evapotranspiration can be maintained for $\psi_s > -10^5$ Pa (pF< 3). It is often assumed that evapotranspiration is reduced at higher potentials ('wetter soil'). However, there are some reasons that in this case potential evapotranspiration can be maintained at rather low soil water potentials ('dry soil).

In the first place, in this silty clay the hydraulic conductivity does not change very drastically for lower soil water potentials. Secondly, because of the large rooting depth (1.0 m for wheat) the root parameter b in eq. (19) is small. This makes the resistance of of the soil (eq. (18)) only limiting for relatively low soil water potentials ('rather dry'). Another reason that potential evapotranspiration is possible for rather dry soil is, that, because of the moderate temperature ($T < 24^{o}$ C) and high relative humidity ($e_a > 0.7\ e_a^*$), evaporative demand of the atmosphere was relatively low ($L.E \approx 0.6\ R_n$).

In Fig. 11 it is shown also that wheat is somewhat less sensitive to limiting soil water supply than potatoes. This is in accordance with other findings (FEDDES and RIJTEMA, 1972).

A sensitivity analysis of daylight evapotranspiration was made for two situations: potential evapotranspiration ($\psi_s = -10^4$ Pa) and reduced evapotranspiration ($\psi_s = -10^6$ Pa, $E/E_{pot} \approx 0.5$). In Table 4 the sensitivity of the evapotranspiration for various parameters is expressed by the derivative. The derivative was calculated in such a way that a linear relation could be assumed. All calculations were performed with the aid of the TERGRA model.

Table 4. Derivatives of daylight evapotranspiration with respect to various parameters for different evapotranspiration conditions

Derivative		Potential evapotr.	Reduced evapotr.
Soil conductivity	dE_d/dK	+ 0.00	+ 0.10
Root parameter	dE_d/db	- 0.00	- 0.15
Plant resistance	dE_d/dR_{plant}	wheat -0.19 potatoes -0.53	- 0.19 - 0.37
Stomatal resistance	dE_d/dr_s	- 0.16	- 0.31
Atmospherical resistance	dE_d/dr_a	+ 0.14	+ 0.14
Water vapour resistance	dE_d/de_a	+ 0.43	+ 0.29
Net radiation	dE_d/dR_n	+ 0.41	+ 0.28

From Table 4 it is seen, that all derivatives have an absolute value <1. This is caused by the many feedback mechanisms of the TERGRA model. Furthermore it can be seen, that in the case of potential evapotranspiration soil parameters are of less importance as compared to the plant, the stomatal and the atmospheric resistance.

Especially the influence of the atmospherical resistance on evapotranspiration is somewhat surprising. Usually it is assumed that potential evapotranspiration decreases when atmospheric resistance increases (PENMAN, 1948). Our results are caused by the fact that for tall crops stomatal resistance is no longer negligible as compared with atmospheric resistance. This holds also for the case of good water supply. Under our conditions we found that stomatal resistance was even larger than atmospheric resistance: $r_s \approx 4\ r_a$. From eq. (29) it is seen, that increasing atmospheric resistance has only a small influence on the toal resistance for water transport: $r_{ah} + r_s$. The resistance for sensible heat flux r_{ah} (eq. (3)) increases, but the total of sensible and latent heat flux (eq. (1)) will hardly change. Therefore crop temperature, and thus also e_c^*, will increase. So the latent heat flux will somewhat increase and the sensible heat flux will decrease.

For small crops with $r_s < r_a$, a change of r_a has little influence on evapotranspiration, because the resistances for sensible and latent heat flux will change with about the same value. Table 4 also gives an indication of the possibilities to simplify the calculations of evapotranspiration. It shows, that potential evapotranspiration is still dependent on stomatal resistance. This means that a model to calculate potential evapotranspiration from atmospherical parameters only will give a very crude approximation of the actual evapotranspiration.

In the TERGRA model the stomatal resistance is calculated from plant and soil resistance, transpiration, incoming radiation and the ψ_l/r_c relation with the eqs. (18-20) and Table 1. For simplifications it should be investigated if an empirical relation can be found between stomatal resistance and some easy measurable parameters, like for instance the reflectivity in the middel-infrared wavelength band.

VI.4. Radiation crop temperature

- Incomplete soil cover: potatoes

For plots with incomplete soil cover the radiometrically measured surface temperature T_r will be composed of the temperatures of canopy and soil. Calculations have been set up with the aid of the expression:

$$T_r = S_c T_c + (1 - S_c)\, T_s \qquad (29)$$

where S_c is the soil coverage that can be detected by infrared photography (section IV) and T_s is the soil surface temperature. The temperatures T_c and T_s have been calculated with the TERGRA model. For June, 14 at flight time the computed temperature values accounted to $T_c = 27^o$ C (300 K) and $T_s = 39^o$ C (312 K). For the potato field with $S_c = 0.56 \pm 0.05$, the radiometrically detected temperature of 33^o C (306 K) appeared to be in remarkable good agreement with the calculations. However, this good agreement may be caused partly by accidental reasons.

The temperature of the irrigated potato field appeared to be 6 K below the value that would be expected from Fig. 8. By means of the TERGRA model also the wet-soil temperature was calculated. As this wet-soil temperature was 13 K below the dry soil temperature, all temperature differences of this potato field can be explained by assuming that the soil was still wet.

With the TERGRA model the temperature difference between a potentially transpiring potato canopy and a potato canopy with zero evapotranspiration was calculated as 4 K. Therefore it is believed that for plots with a certain incomplete soil cover most radiometrically measured temperature differenees will be caused by differences in the soil surface temperature.

- Complete soil cover: wheat

In Fig. 12 radiometrically measured crop temperature T_r at

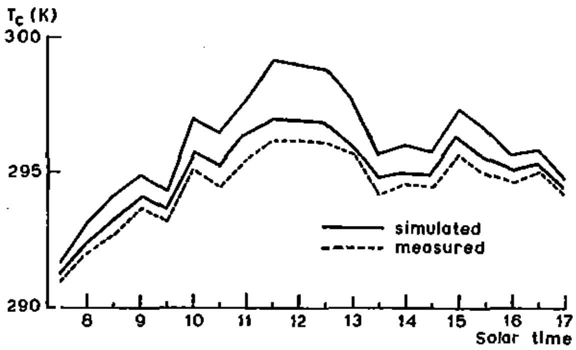

Fig. 12. Radiometrically measured crop temperature of wheat on June, 14 as compared with two TERGRA simulated crop temperature

June, 14 is compared to simulated crop temperature T_c from the TERGRA model for wheat. Simulated crop temperatures have been calculated with and without the correction according to THOM. Fig. 12 shows that large differences between simulated and measured temperatures appear, especially in the case of calculation with the mentioned correction. Reasons causing this discrepancy are summarized in Table 5. It can be seen that the main reasons can be

Table 5. Uncertainties in the determination of crop temperature

Subject	Uncertainty	Reference section
Crop temperature measurement	± 0.3 K	IV
Air temperature measurement	± 0.3 K	IV
Crop roughness for momentum	± 0.8 K	VI. 1
Correction of THOM	± 2 K	III. 1
Crop emissivity	± 0.5 K	VI. 2
Evapotranspiration simulation	± 2 K	VI. 3

found in the simulation of the evapotranspiration and the correction of THOM. Therefore it is recommended that the evapotranspiration will be measured with an other independent method, e.g. Bowen-ratio method, correlation method, etc. Unless the many uncertainties it seems that the above mentioned correction of THOM is very questionable in the case of a wheat canopy. The problems arising from the interpretation of radiometrically measured crop temperature will now be summarized briefly.

In the present approach evapotranspiration is calculated from eq. (17). In this equation the transport of sensible heat is estimated by considering the temperature difference between the air temperature at 2 m height and the radiometrically measured crop temperature. The latter implies some kind of average canopy temperature. In eq. (17), however, it is implicitely assumed that T_c is taken at the height where, according to the logarithmic wind profile theory, the extrapolated wind velocity is zero (see eq. (9)). This is often not the case, even when including the correction of THOM, which extrapolates the temperature profile to a somewhat lower height. Thus the radiometrically measured crop temperature does not necessarily coincide with the crop temperature T_c as used in the sensible heat transport equations.

Also in the present approach only one crop temperature T_c is considered. As viewed in Fig. 7 the radiometrically measured crop temperature, however, depends notably on the angle of observation. Therefore it is recommended to use only one certain anlge of observation, preferably in the direction perpendicular to the surface.

Considering all the problems involved in determining the crop surface temperature it is necessary to go into more detail in the temperature distribution inside the crop canopy. This will enable one to find a proper interpretation of the radiation remperature of a crop and to evaluate how this radiation remperature is connected with the temperature T_c as used in the models. A publication about this subject is in preparation.

VII. SUMMARY

In this study the possibilities were examined of using radiometrically measured crop temperatures for an estimation of evapotranspiration of arable lands.

For crops with incomplete soil coverage a relation between surface temperature and reflectivity was found. This relation may be used to distinguish different moisture situations, especially of the soil surface.

Evapotranspiration of crops with complete soil cover could be estimated with the TERGRA model using the appropriate plant parameters. Especially the stomatal resistance appeared to be an important factor in the calculations.

It turned out that for calculation of evapotranspiration from crop surface temperature the temperature correction for emissivity (although not negligible) was of minor importance only. For tall canopies the errors resulting by taking a wrong crop roughness for momentum also appeared to be rather small.

The radiometrically measured crop temperature, however, deviated considerably from the value as calculated with the TERGRA model.

Therefore it has been stressed that more research must be performed on the physical interpretation of radiometrically measured crop temperatures.

Until then it seems recommendable that temperature differences instead of absolute values must be used to distinguish between different moisture stress situations. Then the interpretation of radiation crop temperature may notably be simplified, as the temperature correction for emissivity and atmospheric disturbances may assumed to be constant for extensive areas. This means, however, that evapotranspiration should be measured on a number of separate test fields, so that the total temperature correction will be estimated for all different crop types.

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