

REMOVAL OF TOPOGRAPHICAL EFFECT FROM REMOTE SENSING DATA FOR THERMAL INERTIA MODELLING

Beata Hejmanowska

University of Mining and Metallurgy al. Mickiewicza 30, 30059 Cracow, Poland

ABSTRACT

Topographical effect was considered in the context of **bare soil moisture assessment**. Soil moisture was evaluated using **thermal inertia modelling**. As an input data in thermal inertia model, the **images in visible and thermal infrared range** are required. Two own programs were worked out *modi* - for thermal inertia modelling and *topo* - for topographical effect removal. Standard GIS software can have an option for topographical effect removal but only using two most popular (but not always correct) methods: Lambert's and Minnaert's.

Theoretical test was performed to qualify significance of the topographical effect in thermal inertia modelling. For soil moisture evaluation on the base of the thermal inertia value, the correction of thermal image seems to be more important than correction of the image in visible range. To study the problem the remote sensing experiment was performed 27.10.1996 for test area (4x4 km) placed near Cracow in Poland. The satellite (Landsat) and airborne images were collected simultaneously with *in situ* measurements of soil moisture and temperature. Experiment was performed near meteorological station where standard meteorological parameters are measured. This kind of data was used for matching thermal inertia model. Conducted investigations confirm that topographical effects can significant influence remote sensing data. Proposed correction bases on assumption that the soils of the same moisture should "look" the same independent of slope and exposition. Topographical effect was easy to observe on the images in visible and infrared range on satellite and on airborne level. Different correction methods were tested for removal topographical effect from remote sensing data. After correction, correlation coefficient between DN and local illumination angle of the surface decreases from approximately 0.50 to 0.04. Initial results of the investigation connected to the influence of topographical effect on remote sensing data used in thermal inertia modelling were presented on the ISPRS Congress in Vienna in 1996. In the paper results of the following researches are presented.

1 INTRODUCTION

Remotely method for soil moisture assessment is not elaborate yet. On the base on the literature: [Choudhury B.J., 1979; Hejmanowska B., Mularz S., 1996; Idso S.B. i in., 1975; Kimball B.A. i in., 1976; 1985; Reginato R.J., i in., 1979] can be stated, that thermal infrared (TIR) is now the most suitable electromagnetic range for soil moisture distinguish. Microwave techniques active as well as passive is hopeful for soil moisture monitoring. These techniques are nevertheless complicated and need still many researches. Therefore using of visible (VIS) and infrared range (IR) seems to be more realistic for remotely assessment of soil moisture. It should be mentioned that images in visible and infrared part of spectrum are easy to access in commercial systems, for example Landsat. Some limitation in applications of Landsat images in Poland is its spatial resolution. 30 m in visible and 120 m in thermal range is a little bit too small for Polish agriculture fields. Improvement of spatial resolution to 15 m in visible and 60 m in thermal range can considerably change this situation. Access to high-resolution satellite images with approximately a few metres will probably cause in Poland seriously increase of interest of satellite remote sensing data. High-resolution images could be competed in compare to airborne images. Especially when we take to account also its revisits cycle, average a few days. Therefore, researches of possibilities of applications of satellite remote sensing images in VIS and IR spectral range are important for Poland as never till now.

Electromagnetic level measured remotely depends on many factors: spectral characteristic of the object, interaction of electromagnetic radiation in the atmosphere, sensor characteristic but also on geometry: direction of sun illumination and sensor viewing direction. Image of the flat horizontal terrain with homogenous covering (forest, or soil, or grass) is different from the

image of the same covering but in hilly area. It is caused by variation of the illumination direction, it means of zenith sun illumination angle. Sun facing slope (southerly) seems to be brighter (warmer) than northerly facing slope. This effect is called "topographical effect". Removal of this "disturbing phenomena" is necessary before for example digital image classification or mathematical modelling of some physical processes (properties) on the earth. In many cases, difference in reflectance coefficient or temperature measured remotely can be caused only by topographical effect. For the objects of the same physical characteristic for example the same water content, we could measure different reflectance or temperature.

Studies of topographical effect removal from remote sensing data in VIS and near infrared (NIR) electromagnetic range are described in the literature. Some theoretical correction methods have been proposed and practical tested. I didn't find any proposal for thermal image correction. Removal of topographical effect bases generally on the assumption that after correction image should be similar to the image of flat horizontal area. So southerly facing slopes should be darker and northerly facing slopes brighter than before correction.

During conducted investigations before following digital processing, remote sensing data were initial corrected to reduce topographical effect. Then the improved images were transformed to thermal inertia image, next correlated with soil water content.

2 METHODOLOGY

Researches contain studies of two problems:

- possibilities of remote sensing assessment of soil moisture on agriculture fields in Poland, and
- necessity of initial correction of remote sensed data to reduce topographical effect.

Soil moisture was estimated basing on thermal inertia parameter defined as:

$$P = \sqrt{kc\rho} \quad (1)$$

where:

k - thermal conductivity,
c – heat capacity,
ρ - soil density.

Thermal inertia P was not evaluated basing on *in situ* measurements of k, c and ρ but was estimated from the remote sensing data:

$$P = f(A_s, \Delta T, B) \quad (2)$$

where:

A_s – short-wave albedo,
ΔT – maximum diurnal temperature differences,
B – additional parameters consist of geographical and meteorological data

Model proposed by Pratt et al. (1980) was used for thermal inertia modeling. In the model the following data are needed:

- Remote sensed images in visible and thermal infrared range,
- Geographical co-ordinates of investigated terrain,
- Imaging date and time,
- Meteorological data.

Obviously proper input data: A_s, ΔT are significant for correctly evaluation of thermal inertia (P). Albedo and maximum diurnal temperature difference should be similar for the same soil moisture of the same soil type. In this moment a problem of initial pre-processing of remote sensing data for topographical effect removal could appear.

Different techniques for reduce topographical effect have been vastly described in the literature. Theoretical models, laboratory measurements of BRDF⁷⁾ and digital corrections of real remote sensing data (mostly of satellite data) are in the literature presented [Cierniewski, J., Verbrugge, M., 1997; Civco, D.L., 1989, Emsile, A.G., Aronson, J.R., 1972, Franklin, J.*et.al* 1986, Hapke, B., 1963; Hugli, H., Frei, W., 1983, Kahle A.B., 1977, Laungcai C., Zingheng L., 1992, Leprieur, C.E., Durand, J.M., 1988, Smith, J.A. *et.al.* 1980]. It should be mentioned that correction methods were concerned to VIS and NIR, and were performed in the mountains, covered by forest, mainly coniferous. During conducted tests, remote sensing images recorded in VIS range were corrected basing on methods known from the literature. Because of lack any proposal for topographical correction in thermal infrared (TIR), the methods from VIS and near IR were implemented to TIR.

Methods for topographical effect removal from remote sensing images in VIS and NIR could be divided on two groups:

- Methods basing on BRDF of the objects,
- Empirical methods.

¹Methods basing on BRDF require *a priori* defined BRDF of the recorded objects. Using empirical methods BRDF don't have to be known.

The following method were practical tested:

- Diffusive method basing on Lambert's law, [Smith, J *et.al.* 1980, Hugli, H., Frei, W., 1983],
- Backscattering method, [Hapke, B.W., 1963, Hugli, H., Frei, W., 1983],
- Minnaert's method, [Smith, J.A., *et.al.*, 1980]
- Empirical method basing on slope exposure.

Diffusive methods assume that the recorded electromagnetic level is independent on sensor direction but is influenced by solar zenith angle. The smaller is zenith illumination angle the greater is recorded electromagnetic level (objects are brighter or warmer) but it's all the same for all sensor position. Correction in the backscattering method bases on assumption that the maximum is observed when sensor has sun behind. Minnaert's method belongs to the empirical methods and is the most popular of them. Empirical method bases of correlation's analysis between DN and illumination parameters, mainly cosines of zenith illumination angle.

Topographical effect was considered for improving remote sensing data before thermal inertia modelling for soil moisture assessment. At the beginning, a theoretical test was performed to check significance of reducing topographical effect in VIS electromagnetic range in compare to TIR range. Topographical effect was also observed during terrestrial measurements using thermal camera AGEMA 780 [Hejmanowska B., Mularz S., 1996]. Maximum difference between temperature of the same soil but measured by camera with sun behind in compare to results from camera sun forward was 20⁰C.

Three level remote sensing experiment was performed to check possibilities of application of thermal inertia (TI) modeling for soil moisture detection in Polish conditions and to check necessity of topographical effect correction. Test area was located in southern part of Poland 50 km east from Cracow (Fig.3). Terrain can be characterized as hilly with elevation from 200 to 300 m above sea level and slopes from 0 to 40⁰. The aim of our research was to estimate soil moisture distribution on the agriculture test fields on the base on remote sensing data. The soils of test area were similar – loess and loess-like. During the experiment, performed 27.10.1996 following data were collected:

- ¼ of Landsat scene,
- airborne panchromatic images (CCD camera) combined with thermal camera (AGEMA 880),
- *in situ* measurements of soil temperature and moisture.

Collected during the experiment data were processed for generate soil moisture map (Fig. 1). Panchromatic and TIR images were pre-processed in GIS system (IDRISI) for radiometrical and geometrical correction. *In situ* measurements of soil temperature were used for calibration and testing TIR images. Geometrical correction was performed using resampling method. After the procedure, images are in proper cartographic co-ordinates. The following step includes topographical effect correction that needs Digital Elevation Model (DEM). DEM for test area were accessible from the project of The Polish Committee of Scientific Research (P 0389/PZ/93/04). The sun co-ordinates can be calculated for date and time of imaging and for latitude and longitude of the test area. Sun position: zenith angle and azimuth calculated for all pixels, for any slope and exposure was used for topographical effect correction. On the base of zenith illumination angle and azimuth, correction coefficient image was constructed (*topo*). Then image was multiply by correction image. In the next step, thermal inertia was generated using program *modi*. For evaluation of parameter B (2), some other data like meteorological data are wanted. Meteorological parameters were obtained from meteorological station. Thermal inertia image was next analysed to find correlation between soil moisture and thermal inertia value in control points. On

⁷⁾ BRDF – Bidirectional Reflectance Distribution Function describe spatial distribution of the radiation coming out from the object.

the base of found function:

$$\text{soil moisture} = \text{function (thermal inertia)} \quad (3)$$

soil moisture image can be generated. After the processing all parameters were statistical analyzed, correlation coefficients between of all the values were calculated.

3 RESULTS

3.1 Influence of topographical correction of remote sensing data for thermal inertia modeling.

Theoretical test was prepared to study significance of topographical correction of remote sensing input data in thermal inertia modeling (Tab.1). Average value of correction coefficient known from the literature could change from 0.6 to 1.6. Influence of topographical effect correction of input images for thermal inertia modeling was only initial mentioned [Gillespie, A.R., Kahle, A.B., 1977]. To compare importance of topographical effect correction of panchromatic image in compare to thermal image following calculation was performed. **All considerations are conducted to soil with the same water content independent of its slope and exposure.** As a reference values, for flat horizontal surface was assumed: $T = 21^{\circ}\text{C}$, and $A_s = 0.2$. When we assumed hypothetical thermal measurements of northerly slopes and assumed of 10% and 20% decrease of temperature (depend of slopes) in compare to horizontal surface, we obtained 18.9°C and 16.8°C . Calculated from this values thermal inertia would be respectively $3588 \text{ J/m}^2\text{Ks}^{1/2}$ and $4277 \text{ J/m}^2\text{Ks}^{1/2}$. When we performed similar calculation for southerly slope assuming increase of temperature by 10% and 20% we obtained $\Delta T = 23.1^{\circ}\text{C}$ and 25.1°C . It causes decreasing of thermal inertia to $2568 \text{ J/m}^2\text{Ks}^{1/2}$ and $2176 \text{ J/m}^2\text{Ks}^{1/2}$. When we perform similar calculation on the base of changing albedo A_s by -10%, -20%, +10%, +20% and stable $\Delta T = 21^{\circ}\text{C}$ one can obtain: thermal inertia form $2829 \text{ J/m}^2\text{Ks}^{1/2}$ to $3231 \text{ J/m}^2\text{Ks}^{1/2}$. On Fig. 2 changes of thermal inertia caused by changes of albedo and maximal diurnal temperature differences on thermal inertia values were presented. Decrease of temperature by 20 % cause increase of thermal inertia by 40%, whereas the same decrease of albedo caused increase of thermal inertia by only 7%. Increase of both albedo and maximum diurnal temperature differences influence thermal inertia more than decreasing of the parameters. This effect is understandably because thermal inertia curves are convergent with increasing of albedo and maximum diurnal temperature differences [Hejmanowska B., Mularz S., 1996, Pratt D. *et.al.*, 1980]. The consideration presented above show how significant can be topographical correction or desist from it. When correction coefficient is respectively: 0.8, 0.9, 1.1, and 1.2 for albedo and thermal images, thermal inertia will be the same for all cases and equal: $3030 \text{ J/m}^2\text{Ks}^{1/2}$. Thermal inertia calculated from uncorrected data can changes from $2829 \text{ J/m}^2\text{Ks}^{1/2}$ to $4277 \text{ J/m}^2\text{Ks}^{1/2}$. It can cause serious consequences when we will calculate soil moisture from the thermal inertia generated from uncorrected input images.

3.2 Remote sensing experiment.

During the experiment, all data were collected as simultaneously as possibly. Airborne panchromatic and

thermal images were simultaneously recorded. Example of the airborne images is on the Fig. 3 presented.

On the image can be noticed:

- meteorological station where normally meteorological parameters are measured,
- 2 small lakes,
- influence of topographical effect on the area covered by grass (southerly slopes are noticeable brighter or warmer than northerly).

Single image covers area approximately $400 \times 330 \text{ m}$. Resolution of airborne images, registered from 1km, was 1m. Soil moisture and temperature were *in situ* measured in 6 control points. Pre-processing phase consists of resampling of archival photogrammetric photos to topographical map in scale 1:25 000 and then resampling of registered images to photogrammetric photo. The procedure was performed because of lack of points possibly to identify both on the image and on the map (small image size). Pre-processing consists also of radiometric pre-correction for transformation of panchromatic image to albedo distribution [Mularz.S, 1990] and thermal images to temperature distribution. Thanks DEM, study of correction of topographical effect was possible. Using DEM zenith illumination angle and azimuth can be calculated for any slope and exposure and for any date and time. For calculation of illumination parameters, correspond to 27 October at 11 a.m., the following values were assumed:

- latitude of test area: $49^{\circ} 59' \text{ N}$,
- longitude of test area:
- sun declination: $-22,5^{\circ}$,
- sun inclination: $-3^{\circ} + 15^{\circ} 1\text{h} = 12^{\circ}$.

Zenith illumination angle on horizontal plane was 73° and azimuth 188° . Elevation of the test area changed from 200 to 300 m above the sea level, slope from 0° to 40° and zenith illumination angle from 50° - 90° (Fig. 6 b). Influence of topographical effect was easy noticeable on both images panchromatic and thermal infrared. Reciprocal correlation between following 4 images were calculated and analyzed:

- albedo and temperature - obtained from panchromatic and thermal images after pre-processing,
- slope and exposure calculated from DEM.

Matrixes of correlation for all the images are presented in Tab.2

On the base of Tab. 2 can be stated:

- thermal level (T) measured by thermal camera are influenced by zenith illumination angle (V_0): $r^2 = 0,36$ - airborne level ($r = -0.63$), $r^2 = 0,26$ - satellite level ($r = -0.51$), when zenith illumination angle increase temperature decrease,
- thermal radiation are correlated with radiation reflected in VIS range, $r^2 = 0,28$ -airborne level ($r = +0.53$), $r^2 = 0.29$ - satellite level ($r = +0.54$); increasing albedo (A_s) follow increasing temperature (T),
- correlation r between albedo (A_s) and zenith illumination angle (V_0) was -0.37 for airborne level and -0.57 for satellite level.
- other variables seem to be uncorrelated, however should be mentioned that only linear correlation was tested and the variable are not linear correlated.

Correlation presented in Tab.2 was calculated for different size of images: airborne and panchromatic. Area shown on topographical map was chosen from satellite image to analyze (Fig. 3 a) and is marked on Fig. 3 b. Airborne image are marked on map (Fig. 3 a), are presented on Fig.3 c and Fig.5.

For particular analysis test field B was chosen (Fig.5). Slope of field B changes from 5 to 20°. Field B has mainly eastern orientation, azimuth changes from 54 - 135°. In profile I-I in seven points, soil moisture and *in situ* temperature were measured. For the profile, I-I correlation between albedo, temperature, zenith illumination angle, surface exposure and slope were calculated (Tab.3). Because of noticeable influence of topographical effect on remote sensing data in VIS and also in TIR some tests were undertaken to reduce this effect. The all mentioned above methods were tested. Images after Lambert's method were over corrected (northerly slopes were too bright and too warm). The better results gave Minnaert's and backscattering method. On the images corrected after Minnaert's and backscattering model could be noticed that correction factor is too significant influenced by slope of the surface in compare to its exposure. Therefore, I tried to consider mainly surface exposure. Correction coefficient was evaluated empirical after compare of albedo and thermal level for different soil exposures and the same water content. After correction, I obtained images on which topographical effect was minimal Fig 6. e. Correlation coefficients between images before and after proposed correction decrease significant:

- panchromatic image r : from -0.32. to 0.16 (airborne level), r : from -0.56 to 0.004 (satellite level),
- thermal image r : from -0.63 to 0.008 (airborne level), r : from =0.51 to 0.0004 (satellite level).

The image influenced minimally by topographical effect was chosen for next processing (Fig.6 e)- soil moisture assessment. Besides images: albedo and temperature meteorological parameters are needed in thermal inertia model. Some of them:

- diurnal air temperature differences: 12.5° C,
- average diurnal air temperature: 2.8° C,
- average wind velocity: 1m/s.

Image of albedo and temperature distribution was used as an input data in thermal inertia modeling using own program: *modi*. Thermal inertia parameter for control points was next statistical analyze to find function describing dependence soil moisture on thermal inertia. Dependence soil moisture/thermal inertia (P) was estimated by linear function:

$$\text{soil moisture} = 0.005422 P - 4.184, \quad r^2 = 0.96 \quad (4)$$

The last step contained transformation of thermal inertia image to soil moisture map.

To evaluate the best parameter for soil moisture assessment all used variables were analyzed (Tab.4). On the base of Tab. can be stated:

1. The highest correlation between soil moisture and albedo was obtained: $r^2=0.98$. High correlation was between soil moisture and temperature measured *in situ*: $r^2=0.94$. Correlation between soil moisture and TI calculated on the base of corrected input data was: $r^2=0.90$ (correlation between temperature calculated from corrected thermal image and soil moisture was $r^2=0.69$. Correction of albedo image caused increase of correlation between soil moisture and albedo from $r^2=0.81$ to 0.98.
2. Correction of thermal image was necessary because of dependence of temperature and soil moisture. Correlation between temperature measured remotely before correction and soil moisture was $r = +0.79$ ($r^2 = 62$) (it is false because means that increasing of soil moisture is connected with increasing of soil temperature, and is contradicted with *in situ*

temperature measurements). After correction correlation coefficient was $r = -0.83$, ($r^2 = 0.69$).

Square means error of soil moisture estimation from thermal inertia model in compare to *in situ* measurements of water content was $\pm 1.47\%$. Because of only 6 control points F-statistic was calculated to check significance of obtained correlation: $r^2 = 0.90$ (4), ($F_{\text{calc}}=95.3$). Estimated from control points linear correlation should be significant because F-Statistic calculated are greater than boundary value $F_{\text{bound}}=7.7$ for $v_1=1$ and $v_2=2$.

At the end, thermal inertia modeling was conducted for uncorrected images. To analyze some northerly facing field was chosen. The field was composed of two parts with different water content about. 10 and 25%. On soil moisture image generated from uncorrected input data water content of analyzed part of control field was reverse (35% and 20%).

4 DISCUSSION

Generally dependence: thermal inertia/soil moisture is not linear in all soil moisture values range, especially in dry and wet state. Testing of thermal inertia /soil moisture function in all values range was not possible because of soil moisture values appearing during the measurements (10-25%)

Known from the literature correlation between images in VIS and near IR concerned homogenous cover type mainly conifer forest (*ponderosa pine*). The high correlation obtained for all the images independent of cover type were caused by late date of imagery (27 October) and low sun position (zenith illumination angle - 73°). For homogenous cover - for example grass correlation coefficient was higher $r^2 = 0.52$ ($r = -0.72$).

5 CONCLUSIONS

Thermal inertia modeling seems to be a suitable tool for soil moisture estimation basing on remote sensing data in Poland. Remote sensing data registered on satellite or airborne level should be initially corrected to reduce topographical effect. Desist from it can strongly disturb soil moisture image. Influence of topographical correction of thermal image seems to be more significant than of panchromatic image. Obtain a proper method for reducing topographical effect from thermal image needs probably many additional investigations.

6 ACKNOWLEDGMENTS

The research described above in this paper were financial supported, in part by Polish Committee of Scientific Research (grant No 9 S605 019 06). Remote sensing experiment was prepared in cooperation with Dr Stanislaw Mularz.

7 LITERATURE

1. Choudhury B.J., 1979 - „Effect of Surface Roughness on the Microwave Emission from Soil” - Journal of Geophysical Research, September 20, Vol.84, No C9.
2. Cierniewski, J., Verbrugge, M., 1997 - „Influence of soil surface roughness on soil bidirectional reflectance” - Int.J.Remote Sensing, 1997, Vol.18, No.6, 1277-1288.

3. Civco, D.L., 1989 - „*Topographic Normalisation of Landsat Thematic Mapper Digital Imagery*”- Photogrammetry Engineering and Remote Sensing, 55 (9): 1303-1309.
4. Gillespie A.R., Kahle A.B., 1977 - „ *Construction and Interpretation of a Digital Thermal Inertia Image*” - Photogrammetric Engineering and Remote Sensing, Vol. 43, No. 8, August 1977, str. 983-1000.
5. Emslie, A.G., Aronson, J.R., 1972 - „*Spectral Reflectance and Emittance of Particulate Materials. 1: Theory*” - Applied Optics, 12 (11): 2563-2572.
6. Franklin, J., Logan, T.L., Woodcock, L.C.E., Strahler, A.H., 1986 - „*Coniferous Forest Classification and Inventory Using Landsat and Digital Terrain Data*” - IEEE Transactions on Geoscience and Remote Sensing, GE-24 (1): 139-149
7. Hapke, B.W., 1963 - „*A Theoretical photometric function for the lunar surface, Journal of Geophysical Research*” - 68 (15): pp. 4571-4586.
8. Hejmanowska B., Mularz S., 1996 - „*Thermal inertia modelling for soil moisture assessment based on remotely sensed data*” - Int. Archives of Photogrammetry and Remote sensing XVII ISPRS Congress , Vienna, Austria,
9. Hejmanowska B., Mularz S., Sitek S., 1997 - „*Soil moisture investigation using remote sensing data and thermal inertia model* ” - The Polish Committee of Scientific Research Nr 9 S605 019 06 (not published),
10. Hugli, H., Frei, W., 1983 - „*Understanding Anisotropic Reflectance in Mountains Terrain*” - Photogrammetry Engineering and Remote Sensing, 49 (5): 671-683.
11. Idso S.B., Jackson R.D., Reginato R.J., 1975 - „*Detection of Soil Moisture by Remote Surveillance*” - American Scientist, September-October 549,
12. Kahle A.B., 1977 - „*A simple model of the earth's surface for geologic mapping by remote sensing*” - Journal of Geophysical Research 82,
13. Kimball B.A., Jackson R.D., Reginato R.J., Nakayama F.S., Idso S.B., 1976 - *Comparison of Field - measured and Calculated Soil - heat Fluxes* - Soil Sci.Soc.Amer.J., Vol 40.
14. Kriebel, K.T., 1977 - „*Measured spectral bidirectional reflection properties of four vegetated surfaces*” - Applied Optics, 17 (2): 253-259.
15. Laungcai C., Zingheng L., 1992 - „*Analysis and correction technique of topographic effect in digital remote sensing image*” - XVII Congress ISPRS, Washington. Commission II. 182-188.
16. Leprieur, C.E., Durand, J.M., 1988 - „*Influence of Topography on Forest Reflectance Using Landsat Thematic Mapper and Digital Terrain Data*” - Photogrammetry Engineering and Remote Sensing, 54 (4): 491-496.
17. Mularz S. 1990 - „*Spectral characteristic catalog of open pit mine formations - Belchatow* “ –project RPBP I.07.II.8NEN AGH, Kraków 1990.: „ Improvement of photogrammetric measurements of open pit mine and of quarry, unpublished
18. Pratt D., Foster S.J., Ellyett C.D., 1980 - „*A Calibration Procedure for Fourier Series Thermal Inertia Model*” - Photogrammetric Engineering and Remote Sensing, No 4, April., pp. 529-538,
19. Reginato R.I., Idso S.B., Vedder I.F., Jackson R.D., Blanchard M.B., Goettelman R., 1979 - „*Soil Water Content and Ewapotranspiration Determined by Thermal Parameters Obtained From Ground - Based*

- and Remote Measurements” - Journal of Geophysical Research, March 20, Vol. .81., No.9,
20. Smith, J.A., Lin, T.L., Ranson, K.J., 1980 - „*The Lambertian assumption and Landsat data. Photogrammetry Engineering and Remote Sensing*” - 46 (9): pp. 1183-1189.

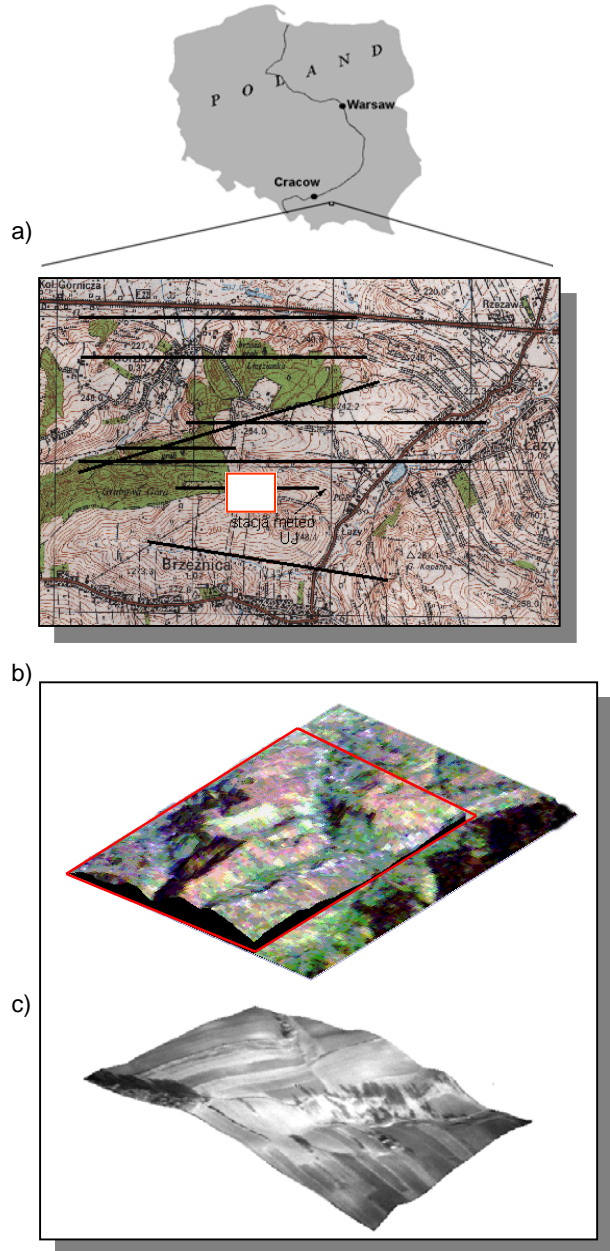


Fig.3 Test area: a) topographical map – with marked airborne image site, b) part of Landsat composition, c) single airborne panchromatic image

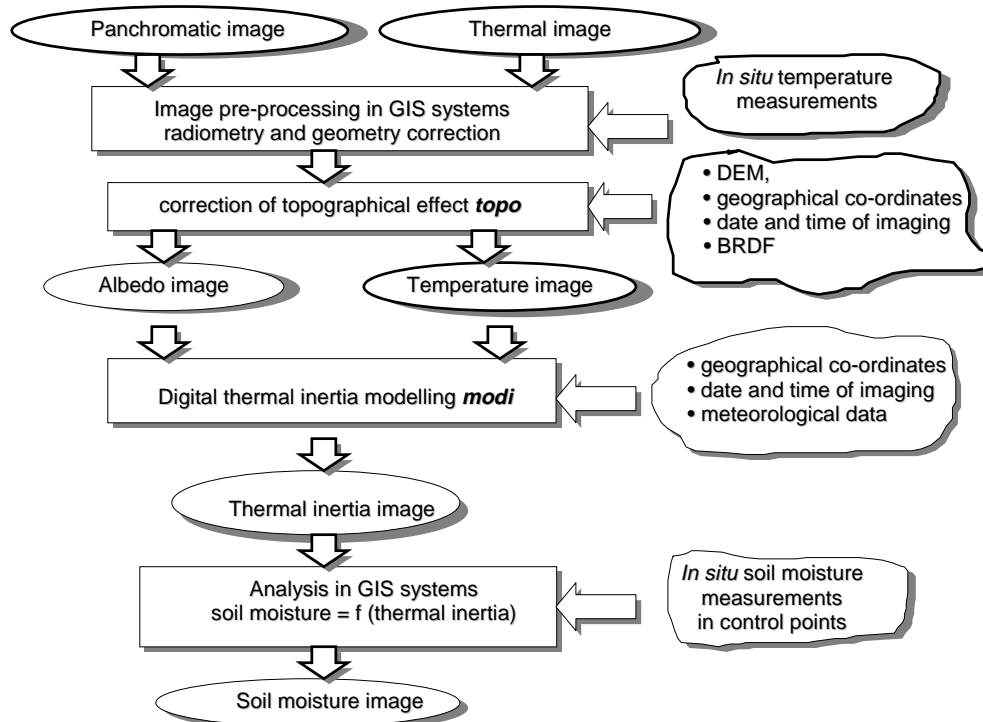


Fig.1. Thermal inertia modelling for soil moisture assessment.

Tab. 1 Influence of temperature (ΔT) and albedo (A) changes on thermal inertia (P)

a)	A (-)	$\Delta T (^{\circ}\text{C})$				
	0,2	16,8	18,9	21,0	23,1	25,1
P ($\text{J/m}^2\text{Ks}^{1/2}$)		4277	3588	3030	2568	2176
b)	$\Delta T (^{\circ}\text{C})$	A (-)				
	21,0	0,16	0,18	0,20	0,22	0,24
P ($\text{J/m}^2\text{Ks}^{1/2}$)		3231	3131	3030	2930	2829

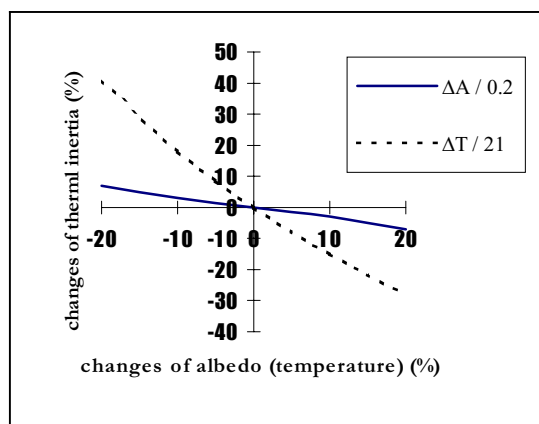


Fig.2 Changes of thermal inertia caused by changes of albedo (temperature).

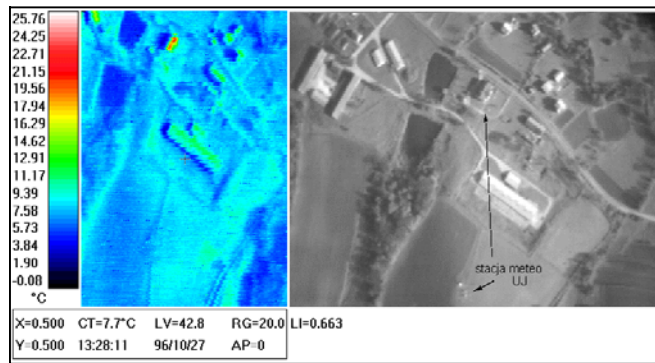


Fig. 4 Example of panchromatic and thermal images (meteorological station)

Correlation matrix (r); a) airborne level b) satellite level. Tab.2

a)	A _s	T	V ₀	A _z	S.
A _s	1	+0,53	-0,32	+0,21	+0,12
T	+0,53	1	-0,63	+0,30	+0,24
V ₀	-0,32	-0,63	1	-0,49	-0,08
A _z	+0,21	+0,30	-0,49	1	+0,25
S.	+0,12	+0,24	-0,08	+0,25	1

b)	A	T	V ₀	A _z	S
A	1	+0,54	-0,57	-0,14	+0,26
T	+0,54	1	-0,51	-0,17	-0,19
V ₀	-0,57	-0,51	1	-0,02	+0,24
A _z	+0,14	-0,17	-0,02	1	+0,18
S.	+0,26	-0,19	+0,24	+0,18	1

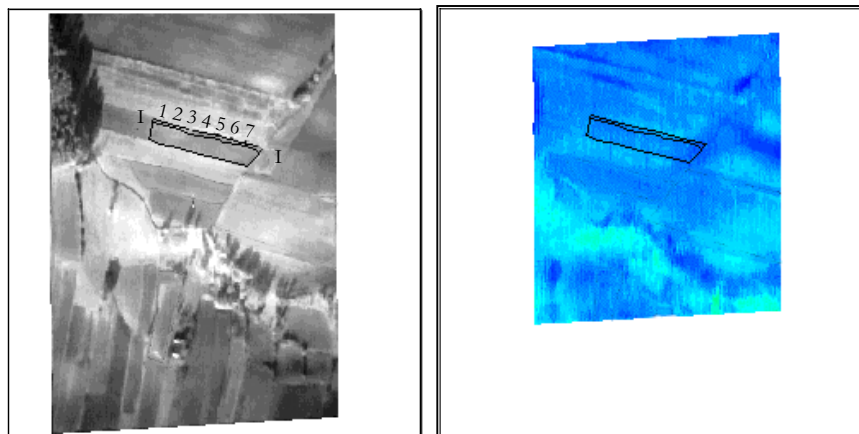


Fig. 5. Panchromatic and thermal mage of test field with marked control points.

Correlation matrix (r) for profile I-I. Tab.3

	A	T	V ₀	A _z	S.
A	1	-0,41	+0,17	-0,18	0,07
T	-0,41	1	-0,50	+0,52	-0,25
V ₀	+0,17	-0,50	1	-0,95	-0,01
A _z	-0,18	+0,52	-0,95	1	-0,03
S.	0,07	-0,25	-0,01	-0,03	1

Summary correlation matrix (r)

Tab.4

	Soil moisture	Albedo (after correction)	Temperature measured remotely (after correction)	Temperature measured <i>in situ</i>	Thermal inertia	Temperature measured remotely (before correction)	Albedo (before correction)
Soil moisture	1	-0.9976	-0.83	-0.97	+0.95	+0.79	-0.90
Albedo (after correction)	-0.9976	1	+0.86	+0.94	+0.95	-0.75	+0.90
Temperature measured remotely (after correction)	-0.83	+0.86	1	+0.68	-0.66	-0.33	+0.56
Temperature measured <i>in situ</i>	-0.97	+0.94	+0.68	1	-0.98	-0.92	+0.94
Thermal inertia	0.95	+0.95	-0.66	-0.98	1	+0.89	+0.89
Temperature measured remotely (before correction)	+0.79	-0.75	-0.33	-0.92	+0.89	1	-0.89
Albedo (before correction)	-0.90	+0.90	+0.56	+0.94	+0.89	-0.89	1

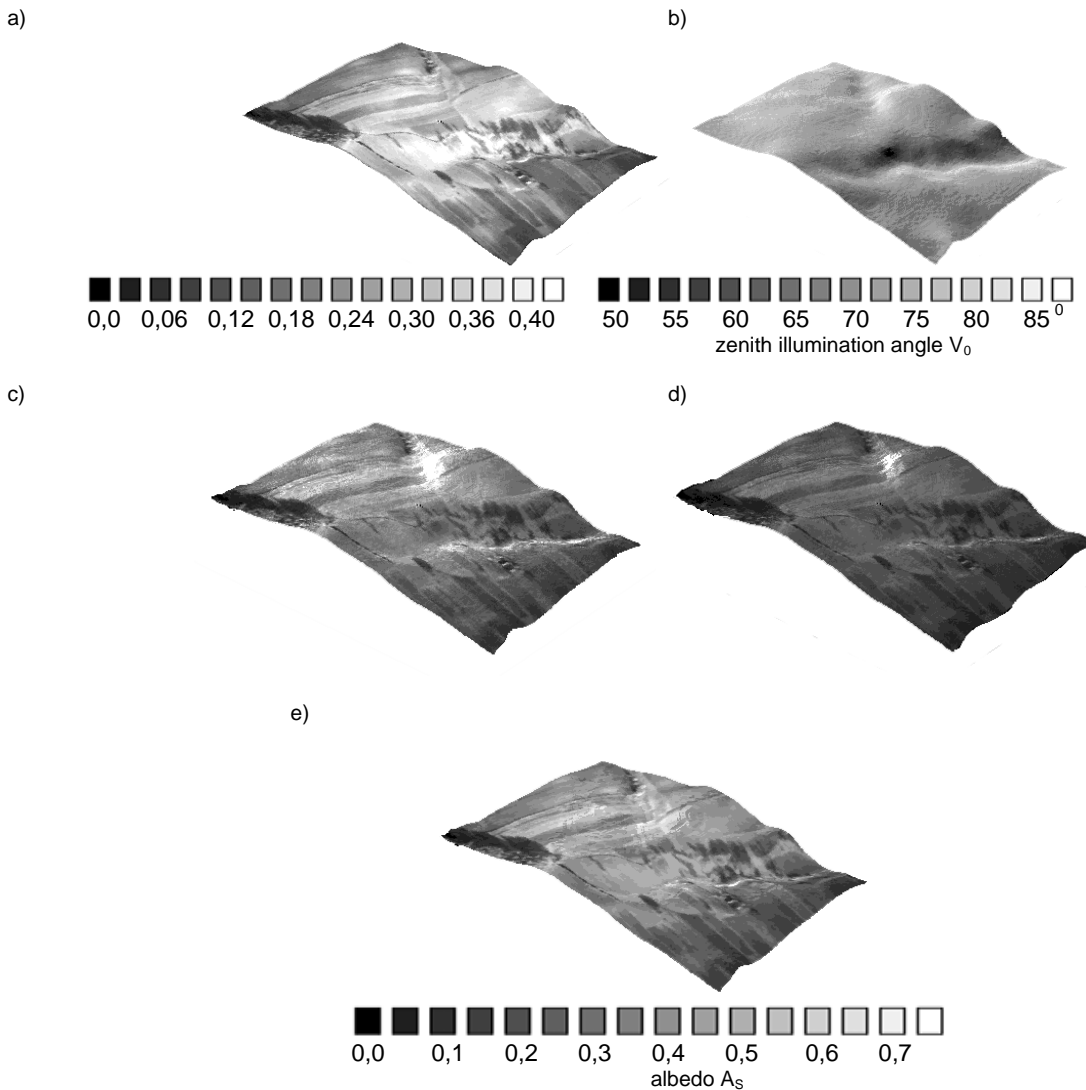


Fig.6. Correction of panchromatic image

- a) registered panchromatic image,
- b) zenith illumination angle (50 - 89°),
- c) image after correction basing on Lambert's model,
- d) image after correction basing on backscattering model,
- e) image after correction basing on azimuth empirical method.

