ON THE FEASIBILITY OF DYNAMIC MONITORING OF TEMPERATURE OF VEGETATIVE CANOPY BY NOAA AVHRR DATA

Xu Xiru, Niu Zheng

Institute of Remote Sensing of Peking University
Beijing, China 100871

SUMMARY:

It is very significant to measure the temperature of vegetative canopy, because it is a key parameter to know the interaction between atmosphere,soil and vegetative canopy which is very useful for drought monitoring, crop yield estimation and so on:
There are three basic difficulties to fulfill this task by infrared band data,the absorption of atmospheric water vapour,the different thermo-emissivity of different ground targets and the mixed pixel problem. Now, we offer a new method to realize this dynamic monitoring of canopy temperature by NOAA-AVHRR data.The error of measurement of canopy temperature may be within 1°k.The basic idea of this method is to suppose the vicinal pixels owning common physical conditions, such as vegetative canopy temperature,soil surface temperature, thermo-emissivity of soil,profiles of atmospheric parameters and so on,to eliminate the complex influence of soil background using the difference of vegetative coverage between two vicinal pixels which creats a favourable condition to cancel atmospheric effect by split window.
This paper also shows that the 1% accuracy of calculation of vegetative coverage is needed if we hope the error of measurement of vegetative canopy temperature within 1°k. An initial result is given,it says it is feasible to measure canopy temperature by AVHRR data.

KEY WORDS: Feasibility, Monitoring, Vegetation, Canopy,Temperature, NOAA-AVHRR.

1. INTRODUCTION

The measurement of land surface temperature by infrared band data is more complicated than the measurement of sea surface temperature because of three main obstacles. They are mixed pixel problem,the complexity of land surface, namely the different ground target owning different emissivity and temperature,and the obvious difference between actual atmospheric conditions and standard atmospheric profile. It is very difficult to get parameter's profile of atmosphere in situ, so it is both complicated and almost imposible to correct atmospheric effect by theoretical calculation. That is the reason why after many years panstaking effort the problem of measurement of land surface temperatrue still wanders on the stage of feasibility study,but it is a very significant parameter which describs the interaction between earth surface and atmosphere, for example, if we can say the monitoring of drought which drives world attention today can be quantitatively monitoring by evapotranspiration model, then it is a key problem to measure temperature of vegetative canopy with high accuracy by remote sensing method. From the creation of this model almost two decades had passed, but till now it does not be used in operation manner, because the key problem have not been solved.
Dr. Wan had analized the possibility to measure the temperature of snow surface, bare soil surface, vegetative canopy etc. by NOAA-AVHRR data. He also pointed out the error possibly within 1°k, but there are two problems,we have to point out here, the mixed pixel problem to be neglected by him and the inverse calculation only based on U.S. standard profile of atmosphere. Obviously, these two assumptions are far from reality.They had seriously damaged its value of application.
The aim of this paper is to discuss the feasibility of measurement of canopy temperatrue without these two unreasonable preconditions. It is very difficult to generally discuss the measurement of land surface temperature, but if our attention to be focused on canopy temperature, it will be feasible.

2. METHOD

2.1 Model

The thermo-emissivity of single leaf reaches 0.98. Since the existence of 'cave effect', it seems that it is reasonable to suppose the thermo-emissivity of vegetative canopy equal to '1'. If we focus our attention to rural area, mixed pixel are consisted of soil background and vegetative canopy, therefore the radiance received by sensor aboard satellite is

$$L = [\ L_b(T_v)a_v + L_b(T_s)(1-a_v)\mathcal{E}_s\ ]\ t_o + \int_{t_o}^{1} L_b(T(Z))dt + (1-\mathcal{E}_s)(1-a_v)t_o^2 \int_{t_o}^{1} \frac{L_b(T(Z))}{t^2}\,dt \quad \ldots\ldots\ldots\ldots(1)$$

where L is the radiance arrived at sensor aboard satellite, L_b represents Planck black body radiative formular, T_v and T_s represent physical temperature of vegetative canopy and soil respectively, a_v means the vegetative coverage in single pixel, $0 \leq a_v \leq 1$, $\mathcal{E}_s$ is the thermo-emissivity of soil, t_o is the transmittance of whole atmosphere, t is the atmospheric transmittance from Z to up boundary of atmosphere, T(Z) and e(Z) means profile of atmospheric temperature and water vapour mass respectively.
We state the physical meaning of every term appeared on the right side of equation (1) as follows: The first term represents the radiance emitted by canopy and soil themself attenuated by atmosphere at last reaching sensor aboard satellite. The second term means upward radiance of atmosphere. The down ward radiance of atmosphere reflected by soil back ground then experienced atmospheric attenuation at last reaching sensor is calculated by third term.
If we are interested in drought monitoring of large area,namely the change with low spatial frequency, therefore we can assume two vicinal pixel owning the same values of T_v, T_s, $\mathcal{E}_s$, T(Z), e(Z) and so on.
"1" and "2" are two vicinal pixel.

$$\Delta L = \frac{L^2(1-a_v^1) - L^1(1-a_v^2)}{(a_v^2 - a_v^1)} = L_b(T_v)\ t + L_b(T(Z))dt \ldots\ldots(2)$$

The number appeared on up right side represents the number of pixel.

Let $L_b(T_b) = \Delta L$

That means using brightness temperature to express the radiance ΔL.

Let
$$
\begin{aligned}
I &= L_b(T_v) - L_b(T_b) \\
&= L_b(T_v) - L_b(T_v)\ t_0 - \int_{\tau_0}^{1} L_b(T(Z))\,dt \\
&= \int_{\tau_0}^{1} [\ L_b(T_v) - L_b(T(Z))\ ]\,dt
\end{aligned}
$$

We apply linear approximation condition, then

$$
I = \int_{\tau_0}^{1} \left(\frac{dL_b}{dt}\right)_{T_v} [\ T_v - T(Z)\ ]\,dt
$$

We have to point out that the difference of temperature between canopy and soil surface is obvious. The temperature of vegetative canopy varys around the air temperature of the same hight, so the linear approximation between $L_b(T_v)$ and $L_b(T(Z))$ is acceptable.

Let
$$
\begin{aligned}
\Delta T &= T_v - T_b \\
&= \frac{I}{\left(\frac{dL_b}{dT}\right)_{T_v}} \\
&= \int_{\tau_0}^{1} [\ T_v - T(Z)\ ]\,dt
\end{aligned}
$$

The atmospheric attenuation of channel 4 and 5 mainly comes from absorption of water vapour. We adopt the approximation that the absorption coefficient of water vapour (K_λ) is constant with hight, then,

$$
\begin{aligned}
\Delta T &= T_v - T_b \\
&= K_\lambda \int_{\tau_0}^{1} [\ T_v - T(Z))\,]\,dm_e \quad \ldots\ldots\ldots\ldots\ldots (3)
\end{aligned}
$$

dm_e means the water vapour mass contained by layer of dZ.

The value of integration on right side of equation (3) is only the function of atmospheric condition and has nothing to do with band frequency chosen by us. Therefore

$$
T_v = T_{b4} + \frac{K_4}{(\ K_5 - K_4\ )} [\ T_{b4} - T_{b5}] \quad \ldots\ldots (4)
$$

Where T_{b4} and T_{b5} are brightness temperature calculated by formula (2) corresponding to channel 4 and 5 respectively.

2.2 How to know the value of a_v ?

The key point of this model is that under the assumption of vicinal pixels taking the same physical conditions to eliminate complicated effect of soil background using the difference of vegetative coverage between two vicinal pixels, then to creat the favourable condition for us to cancel effect of absorption of water vapour within channel 4 and 5 by " split window ". Obviously it is very critical to know the value of a_v for each pixel.

Fig.1 shows us the physical course of radiance of channel 1 and 2 to be received by sensor.

$$
L = L_s + L_0 + L_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)
$$

Where L: the radiance arriving at sensor aborad

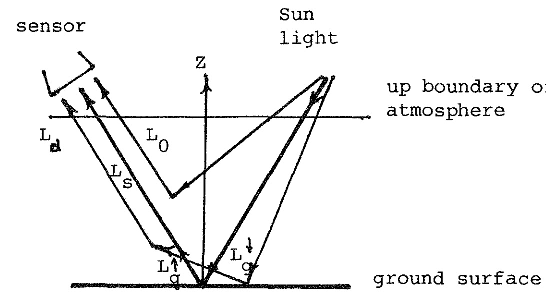

Fig. 1 The physical course of radinace of channel 1 and 2 received by sensor.

satellite.

L_0 : usually we call it path radiance.

L_d : it represants diffuse radiance,since the low resolution the AVHRR has, we had proven that L_d /L is less than 8% and about 95% radiance of L_d comes from four successive pixels. Our results is coordinate with results given by some other authors.

L_s : The radiance carrys signal which we want.It is created by direct sun shine scattered or reflected by target and attenuated by atmosphere.

$$
\begin{aligned}
L_s &= L_g^{\uparrow}\ t_0^{\uparrow} \\
&= \rho\, L_g^{\downarrow} t_0^{\uparrow} \\
&= \rho(\ L_G t_0^{\downarrow} + \frac{E}{\pi}\ )\ t_0^{\uparrow}
\end{aligned}
$$

Where ρ: the bidirectional reflectance factor of ground target. E : the irradiance of sky light, under the assumption of Lambert body for target, then the radiance is equal to E/π .If the visibility of atmosphere is better than 23 KM, the experimental measurement and theoretical calculation show E/π is less than 2% of direct sun radiance ($L_G t_0^{\downarrow}$) for channel 1 and 2. We omitted E/π and the difference between $t_0^{\uparrow}$ and $t_0^{\downarrow}$

$$
L = \rho\, L_G\ t_0^2 + L_0 + L_d
$$

$$
\rho = (\ L - L_0 - L_d\ )/\ L_G\ t_0^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)
$$

According to definition of Perpendicular Vegetation Index (PVI), we have

$$
PVI = \rho_2 \cos\theta - \rho_1 \sin\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)
$$

Where subscript 1 and 2 mean channel 1 and 2. θ is the angle between soil line and coordinat of ρ_1. We had done field measurements of ρ_2 and ρ_1 for different type of soil, soil moisture level and surface roughness. The results are shown in Fig.2.

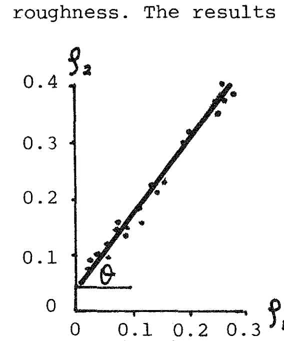

Fig. 2 The soil line

We substitute (6) into (7)

$$PVI = [(L_2 - L_{o2} - L_{s2})/ L_{G2}\, t_{o2}^2 \cos\theta] - [(L_1 - L_{o1} - L_{s1})/ L_{G1}\, t_{o1}^2 \sin\theta] \quad \ldots\ldots (8)$$

From another point of view of mixed pixel, we have

$$\begin{aligned} \rho_2 &= a_v \rho_{2,v} + (1- a_v) \rho_{2,s} \\ \rho_1 &= a_v \rho_{1,v} + (1- a_v) \rho_{1,s} \end{aligned} \quad \ldots\ldots (9)$$

To substitute (9) into (7)

$$PVI = a_v (\rho_{2,v} \cos\theta - \rho_{1,v} \sin\theta) + (1- a_v)^* (\rho_{2,s} \cos\theta - \rho_{1,s} \sin\theta) \quad \ldots\ldots (10)$$

We apply (8) and (10) to pixel 1 and 2 respectively,

$$a_v^2 - a_v^1 = [\frac{\cos\theta}{L_{G2} t_{02}} (L_2^2 - L_2^1) - \frac{\sin\theta}{L_{G1}\ t_{01}} (L_1^2 - L_1^1)]/(\rho_{2,v} \cos\theta - \rho_{1,v} \sin\theta) \quad \ldots\ldots (11)$$

Since L_0 and L_d are almost the same for vicinal pixels, so they can be eliminated by subtract. We should point out here that because of large scale of pixel of AVHRR the value of ($\rho_{2,s} \cos\theta - \rho_{1,s} \sin\theta$) represents an average value of large area, it is allowable to let

$$\rho_{2,s} \cos\theta - \rho_{1,s} \sin\theta \doteq 0$$

$\rho_{2,v}$ and $\rho_{1,v}$ can be measured in the field. Albedo value L_2/L_{G2} and L_1/L_{G1} can be known from AVHRR data. The value of t_{02} and t_{01} can be calculated from visibility in situ. Therefore the value of right side of equation (11) are known. We use symble m to represent it

$$a_v^2 - a_v^1 = m \quad \ldots\ldots (12)$$

From channel 3 , we have

$$L_3 = [L_{b3}(T_v)\ a_v + L_{b3}(T_s)(1- a_v)\ \varepsilon_s]\ t_0 + \int_{\tau_{o3}}^{1} L_{b3}(T(Z))\ dt_3 + (1- \varepsilon_s)(1- a_v)\ t_{03}^2 {}^* \int_{\tau_{o3}}^{1} \frac{L_{b3}(T(Z))}{t_3^2}\ dt_3 + (1- \varepsilon_s)(1- a_v)^* \rho_3\ L_{G3} t_{03}^2 \quad \ldots\ldots (13)$$

The subscript 3 means channel 3. The fourth term on right side of equation (13) represents the contribution of direct sun radiance scattered or reflected by ground target. The meaning of other terms are similar with formular (2). We apply (13) to pixel 1 and 2 , then

$$\Delta L_3 = \frac{L_3^2 (1- a_v^1) - L_3^1 (1- a_v^2)}{(a_v^2 - a_v^1)}$$

$$= L_{b3}(T_v)\ t_{03} + \int_{\tau_{o3}}^{1} L_{b3}(t(Z))dt \quad \ldots\ldots (14)$$

The atmospheric transmittance of channel 3 is much stable than channel 4 and 5. We had chosen two extreme atmospheric conditions from historical records, one represents cold and dry weather, another represents warm and humid day, the program LOWTRAN 7 was applied to calculate atmospheric transmittance. We found the difference of average transmittance of whole atmosphere between two extremes is $\Delta t_{03} = 11.8\%$, but $\Delta t_{04} = 35.1\%$ and $\Delta t_{o5} = 45.6\%$.

The absorption of channel 3 is caused by water vapour(H_2O), nitrogen(N_2) and carbon-dioxygen (CO_2). The changes of transmittance with season of N_2 and CO_2 are very small about 10^{-3} to 10^{-4} for every layer. Five layers model adopted by us (0-2 KM, 2-4 KM, 4-7 KM, 7-10 KM, 10- KM). There are two parts for water vapour absorption, one is called continuative absorption which is almost constant with frequency, the other is called line-shape absorption which owns obvious charracteristics of selective absorption with frequency. Anyway, since the change of channel 3 is stable, if we know T(Z) and e(Z) by radio sound or by TOVS data in situ the linear approximation can be adopted instead of rigorous calculation by LOWTRAN 7. In our experiments the relative error are not larger than 5%.

As for value of $L_{b3}(T_v)t_{03}$, The problem is T_v unknown,but T_v is very near T_a, if we use T_a instead of T_v no serious error will be caused. Up to now the right side of formular (14) can be known. We use n to represent it.

$$\frac{L_3^2(1- a_v^1) - L_3^1(1- a_v^2)}{(a_v^2 - a_v^1)} = n \quad \ldots\ldots (15)$$

We can use formular (12) combined with formular (15) to know a_v^1 and a_v^2 .

2.3 The requirement of accuracy of a_v

It is an essential step to know the value of a_v with high accuracy, otherwise it is impossible to eliminate complex influence of soil by formular (2). In fact, it is also impossible to calculate a_v without error by channel 1,2 and 3 data. Therefore it is an important question how does the error of T_v can be caused by error of a_v ?

In another words, if the error of T_v within 1°K to be required, then what kind accuracy of a_v should be satisfied ? That means we have to know

$$\frac{dT_v}{da_v} = ?$$

Based on formular (4)

$$\frac{dT_v}{da_v} = \frac{dT_{b4}}{da_v} + (\frac{K_4}{K_5 - K_4}) [\frac{dT_{b4}}{da_v} - \frac{dT_{b5}}{da_v}] \quad \ldots\ldots (16)$$

because $\frac{dT_{b4}}{da_v}$ is almost equal to $\frac{dT_{b5}}{da_v}$, therefore $\frac{dT_{b4}}{da_v}$ is a decisive factor for $\frac{dT_v}{da_v}$.

The relationship between T_b and a_v can be described by a complex function.

$$\frac{dT_b}{da_v} = \frac{dT_b}{d(\Delta L)} \frac{d(\Delta L)}{da_v} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

If the amount da_v appeared in denominator term on right side of (17) can be interpreted as an error of calculation of a_v then we can explain the amount $d(\Delta L)$ appeared in the numerato on right side of (17) the error of ΔL caused by error of a_v.

If we use asterisk (*) to represent the amount with error and use Δa_v to express the average square root value of error of a_v

$$a_v^* = a_v + \Delta a_v$$

$$L^* = \frac{L^2(1-a_v^{1*}) - L^1(1-a_v^{2*})}{(a_v^{2*} - a_v^{1*})}$$

its true value is

$$L = \frac{L^2(1-a_v^1) - L^1(1-a_v^2)}{(a_v^2 - a_v^1)}$$

its absolute error is

$$\delta_a = | L^* - L |$$

according to the theory of error analysis,its relative error can be expressed by

$$\delta_r = \frac{a}{|\Delta L^*|} = \frac{2\, L * \Delta a}{2L + 2L\,|\Delta a_v|} + \frac{2\Delta a_v}{2|\, a_v\,|}$$

$$= \Delta a_v \left(\frac{1}{1+a_v} + \frac{1}{a_v} \right) \qquad \ldots\ldots\ldots\ldots (18)$$

for error analysis we take $L^2 = L^1$, $\Delta a_v^2 = \Delta a_v^1$, $a_v^2 = a_v^1$.

The relationship between T_b and ΔL can be described by Planck black body radiance law.

$$\frac{d(\Delta L)}{d\,T_b} = \Delta L \frac{h\,c}{K\lambda} \frac{1}{T_b^2}$$

$$\frac{d(\Delta L)}{\Delta L} = \frac{h\,c}{K\lambda} \frac{1}{T_b^2}\, dT_b \qquad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

In fact $\frac{d(\Delta L)}{\Delta L}$ appeared in the left side of (19) means relative error δ_r.

$$\Delta a_v = \frac{h\,c}{K\lambda} \frac{1}{T_b^2} \frac{(1+a_v)\, a_v}{(1+2\,a_v)} \Delta T_b \qquad \ldots\ldots\ldots (20)$$

Where ,

h : Planck constant 6.63×10^{-34} Js,

C : the velocity of light 3×10^8 m/s,

K : the Boltzmann's constant 1.38×10^{-23} J/K

λ: the wave lenght, we take 11×10^{-6} m,

$T_b = 300°$K, $T_b = 1°$K , $a_v = 1$,

then $\Delta a_v = 0.01$

That means if $\Delta T_b \doteq 1°$k to be required therefore the error of a_v should be within 1%. That is a tough task, but it is still possible, for this, a simulating calculation hand been carried out. We suppose the difference of temperature between soil and canopy is larger than 15°K, $t_{03} = 0.8$, the results show that 1% change of a_v may produce $0.00185\ mw/\ m^2\ cm^{-1} sr$.

For channel 3 of NOAA-AVHRR 11 one grey level means

$0.0015\ mw/\ m^2\ cm^{-1} sr$.

As for channel 1 and 2, the difference of reflectance between soil and vegetation is more than 10% for red band, it is more than 15% for near infrared band, so the 1% change of a_v will produce 0.1% change of albedo of channel 1 and 0.15% change of albedo of channel 2.

One grey level of channel 1 and 2 of NOAA-AVHRR 11 represent 0.095% and 0.090% change of albedo respectively.

We concluded that it is still possible to detect 1% change of a_v by channel 1 ,2 and 3 data.

3. THE INITIAL EXPERIMENTAL RESULTS AND ITS ANALYSIS

It is very difficult to check our results directly , because it is impossible to measure average vegetative canopy temperature in the field with size corresponding to a pixel of AVHRR image. Then an indirect way to be chosen, a small county to be singled out, since the area is not so largr we can suppose the wind speed near ground surface is almost the same for all pixels, the air temperature is the same too, then $T_v - T_a$ is the best factor to express Canopy Water Stress Index(CWSI).

Fig.3 shows us the results of our calculation of $T_v - T_a$ from AVHRR data. The blue colour(cold colour) corresponds the largest positive value of $T_v - T_a$ which means the most dry area, the red colour (warm clour) represents the largest negetive value of $T_v - T_a$ which means less water stress. From cold to warm colour the water stress could be gradually eased. We got this AVHRR image in March 15, 1988. We also got a TM image of this area of March 20,1988. The third conponent of Kauth-Thomas transform can be used to express wetness of soil and vegetation.

$$W = 0.2249\ TM_2 + 0.4036\ TM_3 + 0.2518\ TM_4 - 0.7013\ TM_5 - 0.4573\ TM_7 \quad \ldots\ldots\ldots\ldots (21)$$

The most value of W are negetive. We use red color to represent the largest negetive value which means no water stress. We use blue colour to symblize positive value of W which means the largest water stress. Fig. 4 shows the results of TM for the same area with AVHRR image.
Although it is very difficult to calculate the correlation coefficient exactly because of the large difference of pixel size, but the initial statistical results show the correlation coefficient r between two images is about 0.72.

+ Zhengming,W.,1989. Land surface temperature measurement from space: physical principles and inverse modeling. IEEE. Transaction on Geoscience and Remote Sensing 27(3): 1008-1032.

4. REFERENCES

+ References from **journals:**

Becker,F.,1987. The impact of spectral emissivity on the measurement of land surface temperature from a satellite. Int. J. Remote Sensing 8(10):1509-1522.

Dalu,G.,1985.Emittance effect on remotely sensed sea surface temperature. Int. J. Remote Sensing 6(5):733-740.

Dechamps,P.Y.,et.al.,1980. Atmospheric correction of infrared measurements of sea surface temperature using channels at 3.7,11, and 12 m. Boundary layer Meteorology 18:131-143.

Price,J.C.,1984. Land surface temperature measurements from the split window channels of NOAA -AVHRR. J. Geo. Research 89 D(5):7231-7237.

Singh,S.M.,1988. Estimation of multiple reflection and lowest order adjecency effect on remotely sensed data. Int. J. Remote Sensing 9(9): 1433-1450.

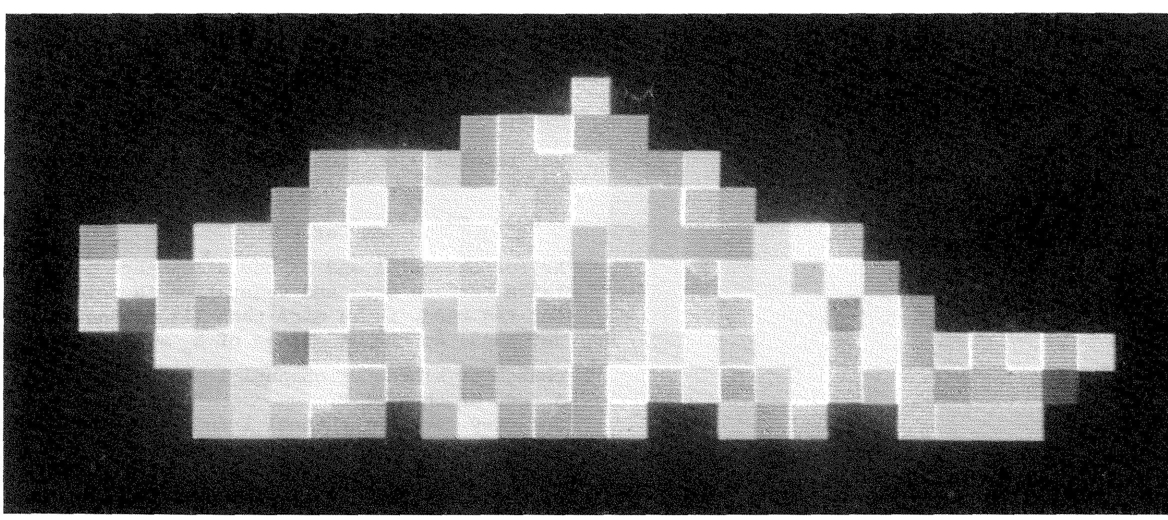

Fig. 3 The distribution map of the value of $T_v - T_a$.

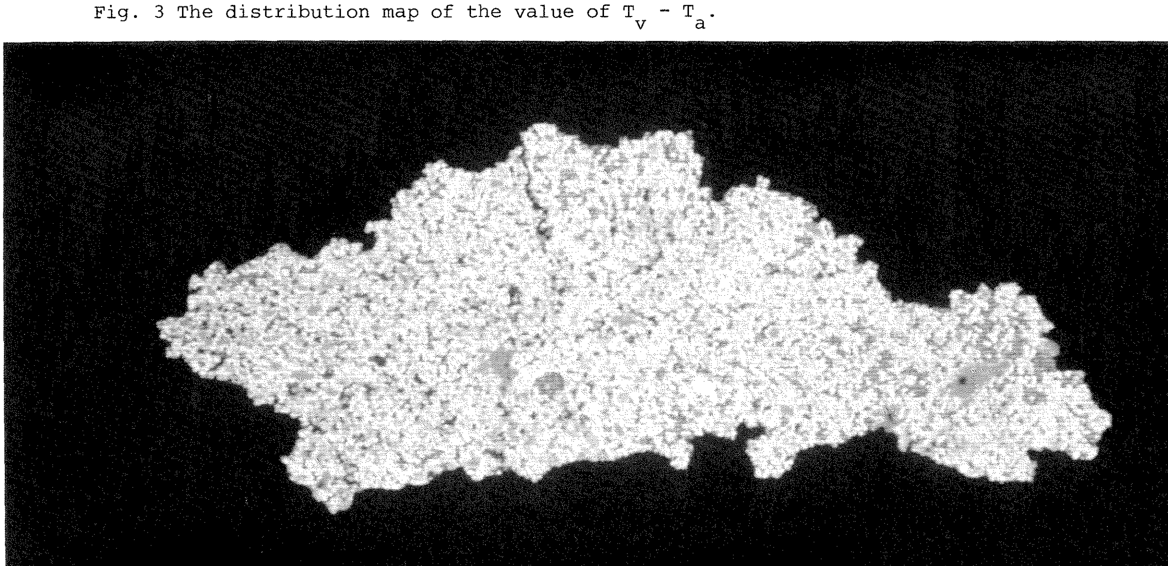

Fig. 4 The distribution map of the value of third conponent of K-T transform W.