ALGORITHMS FOR SIMULTANEOUS DETERMINATION OF LAND SURFACE TEMPERATURES AND EMISSIVITIES FROM SATELLITE RADIATIVE MEASUREMENTS

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1. INTRODUCTION

Accurate land surface temperatures (LSTs) are of fundamental importance for many applications. Deriving LSTs from satellite radiative measurements is desirable, the problem has received wide attention in recent years and many methods have been presented (e.g., Price,1984; Becker,1987; Cooper and Asrar,1989; Becker and Li., 1990; Sobrino et al., 1991; Vidal,1991; Kerr et al., 1992; Ottle and Vidal-Madjar,1992; Ottle and Stoll, 1993; Prata, 1993; Francois and Ottle, 1996; Barducci and Pippi, 1996; Wan and Dozier, 1996). The accurate determination of LSTs is very difficult, that is related to i) the surface upwelling radiance is determined by both the surface temperature and emissivity; ii) the atmospheric effects are always exited; iii) the land surfaces are not uniform, generally. To make atmospheric correction is a difficult task, but in principle it can be done with necessary atmospheric parameters obtained by radiosonde or satellite remote sensing. At present, for most of the algorithms of deriving land surface temperature from satellite measurements, the surface emissivities have to be given previously or assumed. In the 8-14 μm infrared window region, different land surfaces are of different emissivities which may vary in the range of about 0.9-0.99 (Buettner and Kern, 1965; Taylor, 1979; Sutherland, 1986; Nerry et al., 1988; Salisbury and D'Aria, 1992,1994). At present, the knowledge about global land surface emissivities is still very deficient and a difference in surface emissivity of 0.01 may result in a deviation as large as about 2 K in derived land surface temperature (Prata, 1993). Therefore, significant errors might be involved in land surface temperature determination from space by the use of methods with previously given or assumed surface emissivity. The coupling between the surface temperature and emissivity constructs a severe obstacle for the accurate determination of LSTs and the problem has not been properly solved yet. We can not merely rely on selecting proper channels or increasing the number of channels to solve this problem, because of spectral variance of the surface emissivity, there will always be more unknowns than available equations.

Considering that although the surface emissivity is varied from time to time, its variation is relatively slow. Based on the assumption that the change of emissivity is normally negligible in a short period of time, such as one or two days, a two channel method has been presented to determine LSTs and emissivities simultaneously, in which a set of measurement data of two channels (e.g. AVHRR channels 4 and 5) made at two different times, day and night or two continuous days or nights, are used. If there are emissivity variations in two time measurements, but the ratios of emissivity variations for different channels are same, then a three channel method can be used to determine LSTs and emssivities simultaneously.

2. ALGORITHMS

On the basis of radiative transfer theory, the radiance I_i measured in a channel from a satellite-bone infrared sensor for a cloudless atmosphere can be simply expressed as

$$I_i = \varepsilon_i B_i(T_s)\tau_{si} + \rho_i \tau_{si} I_{Di} + I_{Ui} \tag{1}$$

here, ε is the surface emissivity, ρ the surface reflectance, for isotropic surface, ρ = 1-ε , B is the Planck radiance, T_s the surface temperature, τ_s is the path transmittance from the surface to the satellite, I_D is the effective atmospheric downward radiance, and I_U is the upward atmospheric path radiance, the subscript i means that the quantities are weighted average ones considering the response function of channel i. In the thermal infrared window region of 8 - 14 µm, the downward and upward radiances, I_D and I_U , are mainly determined by the atmospheric temperature and moisture profiles, which can be determined by radiosonde or satellite remote sensing. With the necessary atmospheric parameters obtained, the atmospheric transmittance τ_s, the downward and upward radiances, I_D and I_U , can be determined through radiative transfer calculation. The surface upgoing radiance, I_{gi} can be expressed as

$$I_{gi} = \varepsilon_i B_i(T_s) + (1-\varepsilon_i) I_{Di} \tag{2}$$

From Eqs.(1) and (2), I_{gi} can be calculated from measured quantity I_i and calculated quantities, I_{Ui} and τ_{si}, I_{gi} =(I_i-I_{Ui}) / τ_{si} . Hence, in Eq.(2), there are two unknowns, the surface emissivity ε_i and surface temperature T_s. It is clear that ε_i and T_s can not be determined with only one equation, necessary assumptions or more measurements are required.

Many methods use assumed surface emissivity to derive the surface temperature. For this kind of methods, significant error might be involved in derived surface temperatures, because of lack of enough emissivity knowledge about global land surfaces. The coupling problem can also not be solved by means of merely increasing remote sensing channels, because with the number of channels increasing, the unknowns are increasing, too, due to the spectral variation of the land surface emissivity. The land surface emissivity is determined by many factors, such as physical composition, chemical components, geometrical configuration and vegetation state. These factors or some of them may change with time and the surface emissivity may variate, too. Normally, this kind of temporal variation is relatively slow, hence, we can assume that in a short period of time, such as one or two days, these surface conditions can be considered as fixed, then the surface emissivity will not change. Based on this assumption, a two channel algorithm can be used to derived the surface temperature and emissivity, simultaneously.

2.1. Two channel algorithm

When the surface emissivities are not changed at two continuous measurement times (day and night, two days or two nights), $\varepsilon_{ij} = \varepsilon_i$ (i =1,2; j =1,2), similar to Eq.(2), the surface upgoing radiances can be expressed as

$$I_{gij} = \varepsilon_i B_i(T_{sj}) + (1-\varepsilon_i) I_{Dij} \,, \qquad i = 1,2 \;;\; j = 1,2 \tag{3}$$

Here, i refers to channel, j to measurement time. In the system of equations represented by Eq.(3), I_{gij} can be obtained from satellite measured radiances after atmospheric correction, the downward radiance I_{Dij} can be calculated with necessary atmospheric parameters provided. Hence, there are four unknowns, two land surface emissivities ε_i for two channels (i =1,2) and two surface temperatures T_{sj} at two measurement times (j =1,2), and four independent equations, normally, the unique solution can be obtained. From Eq.(3), after canceling the channel emissivities, two equations involved two surface temperatures T_{sj} (j =1,2) can be obtained,

$$a_i B_i(T_{s1}) - B_i(T_{s2}) + d_i = 0 \,, \qquad i = 1,2 \tag{4}$$

here,

$$a_i = (I_{gi2} - I_{Di2}) / (I_{gi1} - I_{Di1})$$

$$d_i = I_{Di2} - a_i I_{Di1} \,, \qquad i = 1,2$$

Define functions f_1 and f_2 as

$$f_i(T_{s1}, T_{s2}) = a_i B_i(T_{s1}) - B_i(T_{s2}) + d_i \qquad i = 1,2 \tag{5}$$

From Eqs. (4) and (5), after making Taylor expansion for f_i, an iterative expression can be obtained,

$$f_i^{k+1} = f_i^k + f_{i1}^k \Delta T_{s1} + f_{i2}^k \Delta T_{s2} \quad , \qquad i = 1,2 \tag{6}$$

The unknown surface temperatures T_{s1} and T_{s2} can be derived with an iterative procedure,

$$T_{sj}^{k+1} = T_{sj}^k + \Delta T_{sj}^k \qquad j = 1,2 \tag{7}$$

$$\Delta T_{s1}^k = (f_2^k f_{12}^k - f_1^k f_{22}^k) / (f_{11}^k f_{22}^k - f_{21}^k f_{12}^k), \tag{8}$$

$$\Delta T_{s2}^k = -(f_1^k + f_{11}^k \Delta T_{s1}^k) / f_{12}^k, \tag{9}$$

$$f_i^k = f_i(T_{s1}^k, T_{s2}^k) \quad , \qquad i=1,2,$$

$$f_{ij}^k = \left(\frac{\partial f_i}{\partial T_{sj}}\right)_{T_{sj}^k} , \qquad i=1,2; \quad j=1,2$$

here, k refers to the iterative time. After the two surface temperatures T_{s1} and T_{s2} to be determined, the two channel emissivities ε_i (i =1,2) can be obtained from Eq.(3),

$$\varepsilon_i = \frac{I_{gij} - I_{Dij}}{B_i(T_{sj}) - I_{Dij}} , \tag{10}$$

2.2 Three channel algorithm

When there are some variations of land surface emissivities at two continuous measurement times, the aforementioned two channel algorithm would not be able to determine land surface temperatures and emissivities exactly. In that cases, a three channel algorithm, in which a pair of three channel measurements made at two continuous times are used, can be used to determine the surface temperatures and emissivities, simultaneously, if the surface emissivities are varied with similar proportionality for different channels. Similar to Eq.(3), the surface upgoing radiance for ith channel and jth measurement can be expressed as

$$I_{gij} = \varepsilon_{ij} B_i(T_{sj}) + (1 - \varepsilon_{ij}) I_{Dij} \quad , \quad i = 1,2,3 \, ; \; j = 1,2 , \tag{11}$$

Because the proportionalities of emissivities at two measurement times for the three channels are assumed to be equal, i.e. $\varepsilon_{i2} / \varepsilon_{i1} = c_i$ (i =1,2,3), $c_1 = c_2 = c_3 = c$, the following expression can be derived from Eq.(11),

$$a_i (B_i(T_{s1}) - I_{Di1}) = c(B_i(T_{s2}) - I_{Di2}) \quad , \qquad i = 1,2,3 \, ; \tag{12}$$

$$a_i = \frac{I_{gi2} - I_{Di2}}{I_{gi1} - I_{Di1}} .$$

After cancellation of the proportionality c, the following two expressions can be obtained,

$$f_1(T_{s1}, T_{s2}) = 0 , \tag{13}$$

$$f_2(T_{s1}, T_{s2}) = 0 , \tag{14}$$

here, the two functions f_1 and f_2 are defined as

$$f_1(T_{s1},T_{s2}) = a_1(B_1(T_{s1}) - I_{D11})(B_2(T_{s2}) - I_{D22}) - a_2(B_2(T_{s1}) - I_{D21})(B_1(T_{s2}) - I_{D12}), \qquad (15)$$

$$f_2(T_{s1},T_{s2}) = a_3(B_3(T_{s1}) - I_{D31})(B_2(T_{s2}) - I_{D22}) - a_2(B_2(T_{s1}) - I_{D21})(B_3(T_{s2}) - I_{D32}). \qquad (16)$$

From Eqs.(13), (14), (15) and (16) the surface temperatures, T_{s1} and T_{s2}, can be determined through an iterative procedure,

$$T_{sj}^{k+1} = T_{sj}^k + \Delta T_{sj}^k \quad , \qquad j = 1,2$$

$$\Delta T_{s1}^k = (f_2^k f_{12}^k - f_1^k f_{22}^k) / (f_{11}^k f_{22}^k - f_{21}^k f_{12}^k),$$

$$\Delta T_{s2}^k = -(f_1^k + f_{11}^k \Delta T_{s1}^k) / f_{12}^k,$$

$$f_i^k = f_i(T_{s1}^k, T_{s2}^k) \quad , \qquad i=1,2,$$

$$f_{ij}^k = \left(\frac{\partial f_i}{\partial T_{sj}}\right)_{T_{sj}^k} , \qquad i=1,2; \quad j=1,2$$

After the surface temperatures are obtained, the surface emissivities can be determined from Eq.(11),

$$\varepsilon_{ij} = \frac{I_{gij} - I_{Dij}}{B_i(T_{sj}) - I_{Dij}} , \qquad i=1,2,3; \quad j=1,2$$

3. SIMULATION TEST

In the following simulation tests, only the coupling problem between the land surface temperature and emissivity is considered, the surface upgoing radiances and the effective downward sky radiances are treated as known quantities.

3.1 Two channel method

For two channel algorithm tests, the AVHRR channels 4 and 5 centered at 930.58 cm^{-1} and 848.18 cm^{-1} are used. Some test results are given in Table 1. In Table 1, the different land surface conditions are represented by the surface temperature T_{sj}, the surface emissivity ε_{ij} and the ratio of emissivities at two measurement times, c_i ($c_i = \varepsilon_{i2} / \varepsilon_{i1}$); the different atmospheric conditions are represented by the symbol R_{ij}, which is the ratio of the downward sky radiance to the surface Planck function ($R_{ij}=I_{Dij} / B_i(T_{sj})$). The subscripts i and j refer to ith channel and jth measurement, respectively. The deviations between the derived and "true" surface temperatures and emissivities are indicated by symbols ΔT_{sj} and $\Delta\varepsilon_i$. From Table 1 it can be seen when the surface emissivities of the two channels are unchanged at two measurement times, the temperatures and emissivities can be determined exactly; while there are emissivity variations ($c_1 \neq 1.0$ and/or $c_2 \neq 1.0$), the surface temperatures and emissivities can not be determined exactly, and generally, the deviations increased with the extent of emissivity variation.

Table 1. Results of Retrieval Tests with Two Channel Algorithm
(with AVHRR ch4 and ch5 (930.58 cm^{-1} and 848.18 cm^{-1}))

Case	1	2	3	4	5	6
R_{11}	0.185	0.385	0.385	0.385	0.385	0.385
R_{12}	0.220	0.430	0.430	0.430	0.430	0.430
R_{21}	0.230	0.420	0.420	0.420	0.420	0.420
R_{22}	0.300	0.450	0.450	0.450	0.450	0.450
Ts_1	290.0	270.0	270.0	270.0	270.0	270.0
Ts_2	320.0	290.0	290.0	290.0	290.0	290.0
ε_{11}	0.935	0.975	0.935	0.935	0.935	0.935
ε_{21}	0.970	0.930	0.960	0.960	0.960	0.960
c_1	1.0	1.0	1.002	1.01	0.990	1.012
c_2	1.0	1.0	1.002	1.01	0.991	1.010
ΔTs_1	0.00	0.00	-0.20	-0.79	-0.78	0.91
ΔTs_2	0.00	0.00	-0.14	-0.49	-1.18	1.41
$\Delta\varepsilon_1$	0.00	0.00	0.006	0.023	0.022	-0.025
$\Delta\varepsilon_2$	0.00	0.00	0.006	0.022	0.022	-0.024

3.2 Three channel method

Three channels centered at 930.58 cm^{-1}, 900.10 cm^{-1} and 848.18 cm^{-1} are used to test the three channel algorithm. Some examples are given in Table 2, in which the symbols are of similar meanings as in Table 1. Table 2 shows that the surface temperatures and emissivities can be determined exactly, when the surface emissivities are varied with time with same proportionality for all of the three channels. Otherwise, only approximate results can be derived, but good accuracy can still be obtained, if the temporal variation of surface emissivity itself is small or the differences of temporal emissivity variations between different channels are not significant. With three AVHRR channels, similar results can also be obtained.

Table 2. Results of Retrieval Tests with Three Channel Algorithm
(with 3 channels centered at 930.58 cm^{-1} , 848.18 cm^{-1} and 900.10 cm^{-1})

Case	1	2	3	4	5
R_{11}	0.485	0.485	0.185	0.185	0.185
R_{21}	0.53	0.53	0.33	0.30	0.30
R_{31}	0.42	0.42	0.22	0.24	0.24
R_{12}	0.50	0.50	0.22	0.21	0.21
R_{22}	0.57	0.57	0.37	0.36	0.36
R_{32}	0.44	0.44	0.24	0.28	0.28
Ts_1	330.0	330.0	275.0	280.0	280.0
Ts_2	320.0	320.0	290.0	310.0	310.0
ε_{11}	0.955	0.955	0.905	0.930	0.930
ε_{21}	0.940	0.940	0.980	0.980	0.980
ε_{31}	0.965	0.965	0.935	0.965	0.965
c_1	1.01	1.011	1.012	0.981	0.99
c_2	1.01	1.010	1.010	0.983	0.99
c_3	1.01	1.011	1.011	0.982	0.99
ΔTs_1	0.0	-0.64	-0.25	0.57	0.00
ΔTs_2	0.0	-0.29	0.31	1.29	0.00
$\Delta\varepsilon_1$	0.0	0.015	0.005	0.002	0.00
$\Delta\varepsilon_2$	0.0	0.015	-0.005	0.002	0.00
$\Delta\varepsilon_3$	0.0	0.013	0.002	0.005	0.00

4. CONCLUSION

Because of lack of knowledge about global land surface emissivity, it is of great importance to derive the land surface temperature and emissivity from satellite measurements, simultaneously. Through preliminary simulation tests, it seems encouraging to use the aforementioned two or three channel algorithms to determine land surface temperature and emissivity from satellite measurements made at two continuous times, if the variations of land surface emissivity are negligible or of same proportionality for different channels in a short period of time. Of course, further validation with satellite data is undoubtedly necessary.

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