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The Influence of the Viewing Geometry of Bare Rough Soil Surfaces on Their Spectral Response in the Visible and Near-Infrared Range

Jerzy Cierniewski
Adam Mickiewicz University, Institute of Physical Geography, Poland

This work is a supplement to the article "A model for soil surface roughness influence on the spectral response of bare soils in the visible and near-infrared range" [Remote Sens. Environ. 23:97–115 (1987)]. It contains new equations necessary to calculate the shadowing coefficient of bare rough soil surfaces observed by a sensor from arbitrary angles and directions.

INTRODUCTION

The influence of the degree of soil surface roughness and the solar illumination of soil (defined by the solar altitude, the angle of a slope, and the sloping of the soil surface relative to the sunbeam direction) on soil reflectance in the visible and near-infrared range has been discussed in this journal (Cierniewski, 1987). This influence has been modeled with the assumption that soil reflectance is strongly correlated with the self-shadowing of soil surface. It only referred to a situation when bare rough soil surfaces are observed by a sensor from the nadir.

The present article is prepared as a supplement to the previous one. It contains new equations which enable the calculation of the shadowing of soil surfaces observed by a sensor from any direction above simulated soils. The position of the sensor is defined by the zenithal observation angle and the observation direction in relation to the solar direction.

NEW EQUATIONS

The unit of area (A_u) in Eq. (1*),[1] describing the roughness factor (RF_m) of the simulated structure (Fig. 1), is defined as

$$A_u = d^2 \cos\gamma_s, \tag{1*}$$

where γ_s = algebraic sum of the zenith observation angle (θ) and slope angle (γ). The γ_s value depends on the relationship of the observation direction of the simulated soil surface relative to the solar direction ($D_{o/s}$) and the relation of the θ and γ angles ($R_{\theta/\gamma}$) (see Table 1). Thus, the distance between spheres (d) [Eq. (2*)] is given by the equation:

$$d = \frac{\phi}{2}\left(\frac{\pi}{RF_m}\cos\gamma_s\right)^{1/2}. \tag{2*}$$

[1]Numbers of equations with asterisks follow those from the previous paper (Cierniewski, 1987).

Address correspondence to Jerzy Cierniewski, Adam Mickiewicz University, Institute of Physical Geography, ul. Fredry 10, 61-701 Poznan, Poland.
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655 Avenue of the Americas, New York, NY 10010

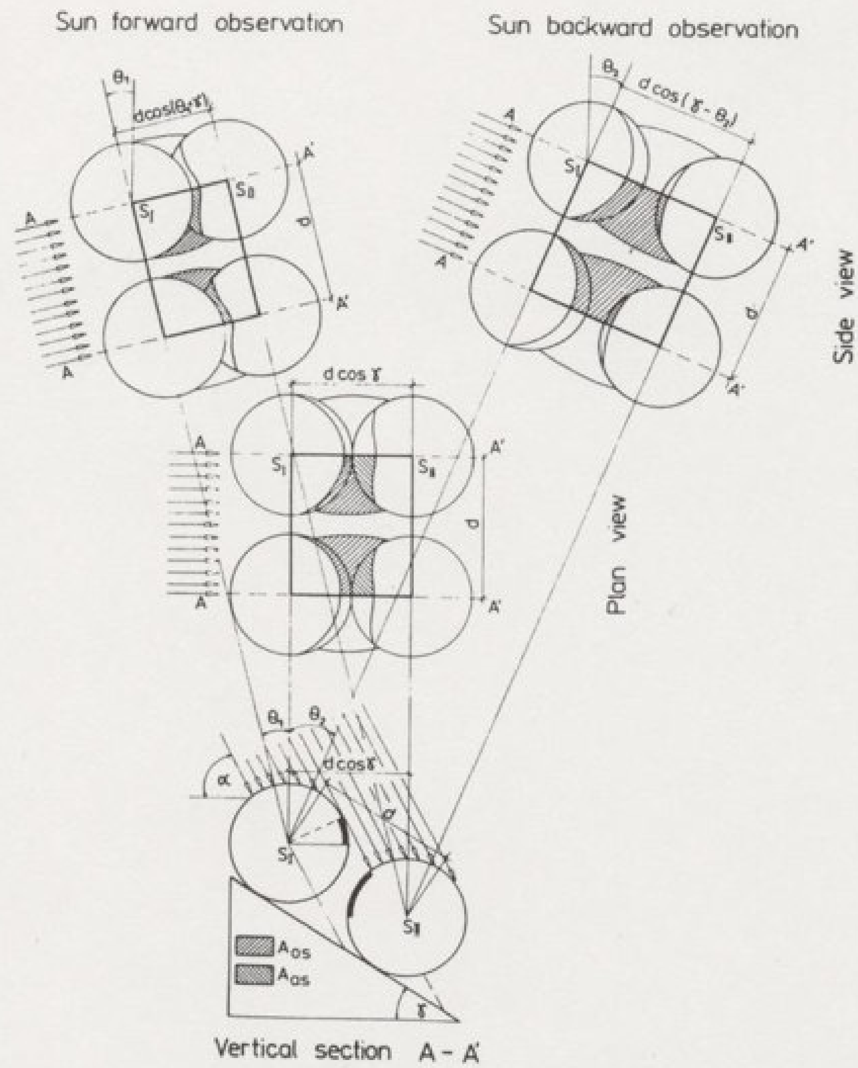

Figure 1. Geometry of the simulated soil surface shadow for calculation of the roughness factor (RF_m) and the shadowing coefficient (SC_m).

The distance of the shadow ellipse center from the given sphere center (d_e) and the major axis of the shadow ellipse (a_e) in a view corresponding to any observation direction depends not only on the slope of the soil surface relating to the solar direction (S) as in Eqs. (4*) and (5*), but also on $D_{o/s}$ and $R_{\theta/\gamma}$ (Fig. 2). They are expressed by the formulas in Table 2.

The A_c shadow component from Eq. (8*) depends on $D_{o/s}$ and the relation of the θ and α angles ($R_{\theta/\alpha}$) (see Table 3). The $r_{\min}$ formula (Fig. 3) was found from the equation

$$y = \pm \tan \alpha_s x + \frac{r}{\cos \alpha_s} + d(\pm \sin \gamma_s \pm \cos \gamma_s \tan \alpha_s),$$

where α_s = algebraic sum of zenith observation angle (θ) and solar altitude angle (α). α_s depends on $D_{o/s}$ and $R_{\theta/\alpha}$ (see Table 4). The $r_{\min}$ value also depends on the sloping (S) and the $R_{\theta/\gamma}$ relation (see Table 5). The choice of the proper formula describing the position of the X_{ri} point from the equations defined as in Table 6 should

Table 1.

$D_{o/s}$	$R_{\theta/\gamma}$	
	$\theta \geqslant \gamma$	$\theta < \gamma$
C	$\gamma_s = \theta + \gamma$	$\gamma_s = \theta + \gamma$
O	$\gamma_s = \theta - \gamma$	$\gamma_s = \theta - \gamma$

C = forward $D_{o/s}$ (observation direction convergent with sunbeam direction) and O = backward $D_{o/s}$ (observation direction opposite to solar direction).

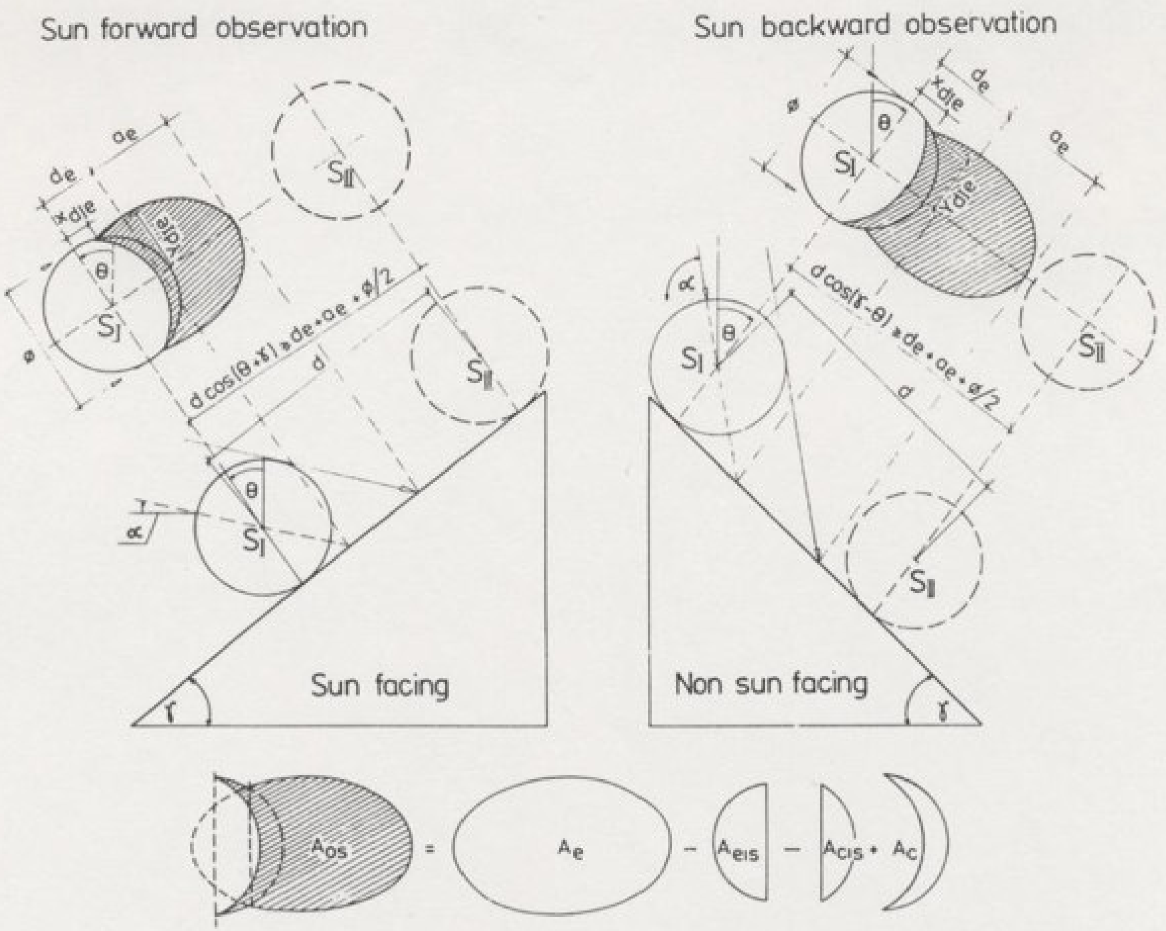

Figure 2. Geometry of an own-sphere shadow and a shadow on a slope plane cast by a given sphere.

Table 2.

S	$D_{o/s}$	$R_{\theta/\gamma}$	*Element of Shadow Area*	
F	C	$\theta \geqslant \gamma$	$d_e = \frac{\phi}{2}\cos\gamma_s\left[\tan(90-\alpha-\gamma)-\tan\gamma_s\right]$	(4a*)
F	C	$\theta < \gamma$ }		
F	O	N }	$d_e = \frac{\phi}{2}\cos\gamma_s\left[\tan(90-\alpha-\gamma)+\tan\gamma_s\right]$	(4b*)
F	N	N	$a_e = \frac{\phi}{2}\frac{\cos\gamma_s}{\cos(90-\alpha-\gamma)}$	(5a*)
B	C	N }		
B	O	$\theta < \gamma$ }	$d_e = \frac{\phi}{2}\cos\gamma_s\left[\frac{1}{\tan(\alpha-\gamma)}-\tan\gamma_s\right]$	(4c*)
B	O	$\theta \geqslant \gamma$	$d_e = \frac{\phi}{2}\cos\gamma_s\left[\frac{1}{\tan(\alpha-\gamma)}+\tan\gamma_s\right]$	(4d*)
B	C	$\theta \geqslant \gamma$	$a_e = \frac{\phi}{2}\cos\gamma_s\left[\frac{1+\cos(\alpha-\gamma)}{\sin(\alpha-\gamma)}-\tan\gamma_s\right]$	(5b*)
B	C	$\theta < \gamma$ }		
B	O	N }	$a_e = \frac{\phi}{2}\frac{\cos\gamma_s}{\sin(\alpha-\gamma)}$	(5c*)

F = forward (sun-facing) slope, B = backward (non-sun-facing) slope, N = nonlimiting $R_{\theta/\gamma}$ relation, α = solar altitude.

Table 3.

$D_{o/s}$	$R_{\theta/\alpha}$	Element of Shadow Area	
C	N	$A_r = \pi \frac{\phi^2}{8}[1 - \sin(\theta + \alpha)]$	(8a*)
O	$\theta \geqslant \alpha$	$A_r = \pi \frac{\phi^2}{8}[1 + \sin(\theta - \alpha)]$	(8b*)
O	$\theta < \alpha$	$A_r = \pi \frac{\phi^2}{8}[1 - \sin(\alpha - \theta)]$	(8c*)

take into account the influence of the same factors as above.

The shadow area fragment A_{sc} is given by the new formula:

$$A_{sc} = \frac{1}{2}\left[\phi^2 \arccos \frac{d \cos \gamma_s}{\phi} - d \cos \gamma_s \left(\phi^2 - d^2 \cos \gamma_s\right)^{1/2}\right], \quad (19^*)$$

with the limitation that A_{sc} only refers to the backward (non-sun-facing slope when $\phi > d \cos \gamma_s$.

RESULTS

The results of the soil surface shadowing simulation by the new equations are presented on exam-

Table 4.

$D_{o/s}$	$R_{\theta/\alpha}$: $\theta \geqslant \alpha$	$\theta < \alpha$
C	$\alpha_s = \theta + \alpha$	$\alpha_s = \theta + \alpha$
O	$\alpha_s = \theta - \alpha$	$\alpha_s = \alpha - \theta$

ples of observation conditions referring to the zenith observation angles (θ) of 0° (nadir), 10°, and 30° both for forward and backward observation directions (Fig. 4). The shadowing coefficient of soil surface (SC_m) reaches values from 1 to 0. The SC_m value of 1 means a complete shadowing of soil surfaces on backward slopes illuminated by direct sunbeams falling at a lower solar altitude (α) than the slope angle (γ), as follows from the equation

$$\alpha_{SC_m = 1} \leqslant \gamma. \quad (1)$$

The value of 0 refers to situations when the shadowed fragments of an illuminated soil are not visible to a sensor from a given direction of its observation. The shadowing coefficient is 0 if the soil surfaces are observed from the direction convergent to the solar direction. The greater the zenith observation angle (θ), the lower the solar

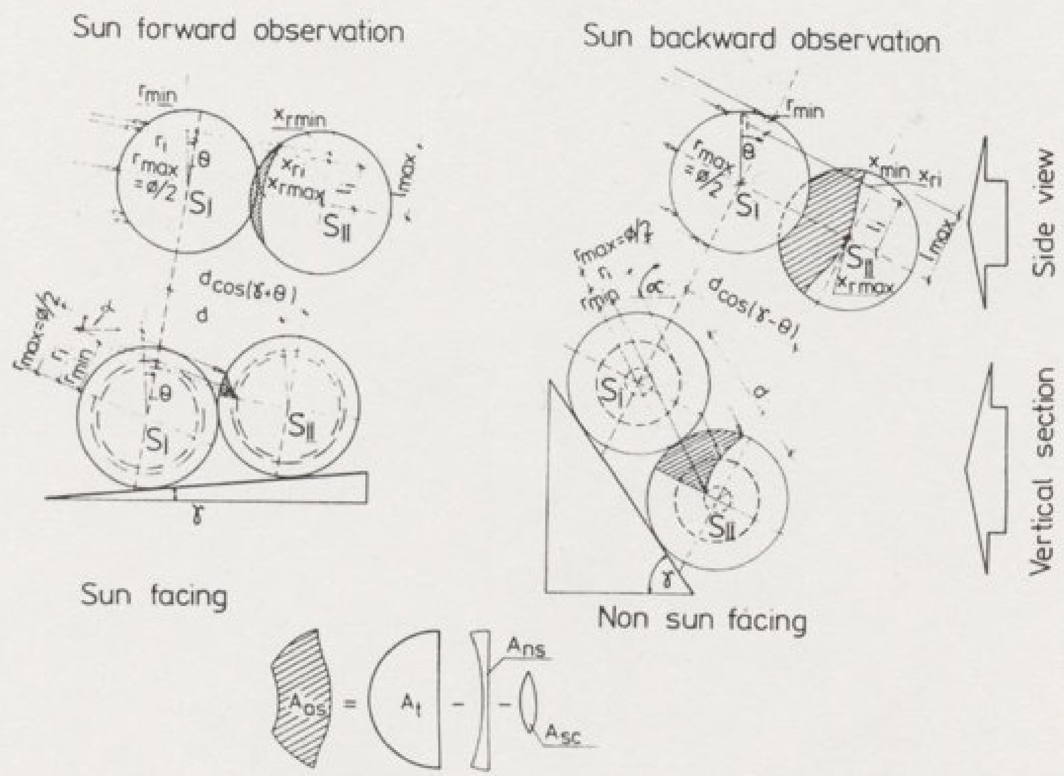

Figure 3. Geometry of a shadow on a sphere cast by an adjoining sphere.

Table 5.

S	$D_{o/s}$	Relation of Angles θ/γ	Relation of Angles θ/α	Element of Shadow Area	
F	C	$\theta \geqslant \gamma$	N	$r_{min} = d \cos\alpha_s \dfrac{-\sin\gamma_s + \cos\gamma_s \tan\alpha_s}{1+\sin\alpha_s}$	(14a*)
F	C	$\theta < \gamma$	N	$r_{min} = d \cos\alpha_s \dfrac{\sin\gamma_s + \cos\gamma_s \tan\alpha_s}{1+\sin\alpha_s}$	(14b*)
F	O	N	$\theta \geqslant \alpha$	$r_{min} = d \cos\alpha_s \dfrac{\sin\gamma_s - \cos\gamma_s \tan\alpha_s}{1-\sin\alpha_s}$	(14c*)
F	O	N	$\theta < \alpha$	as (14b*)	
B	C	N	N	as (14a*)	
B	O	$\theta \geqslant \gamma$	$\theta \geqslant \alpha$	as (14c*)	
B	O	$\theta < \gamma$	$\theta \geqslant \alpha$	$r_{min} = d \cos\alpha_s \dfrac{-\sin\gamma_s - \cos\gamma_s \tan\alpha_s}{1-\sin\alpha_s}$	(14d*)
B	O	$\theta \geqslant \gamma$	$\theta < \alpha$	as (14b*)	
B	O	$\theta < \gamma$	$\theta < \alpha$	as (14a*)	

Table 6.

S	$D_{o/s}$	Relation of Angles θ/γ	Relation of Angles θ/α	Element of Shadow Area	
F	C	$\theta > \gamma$	N	$X_{ri} = -\cos^2\alpha_s\left[\dfrac{r_i \tan\alpha_s}{\cos\alpha_s} - dM\tan\alpha - \left(\dfrac{2r_i dM}{\cos\alpha_s} - d^2M^2\right)^{1/2}\right]$ $M = -\sin\gamma_s + \tan\alpha_s \cos\gamma_s$	(16a*)
F	C	$\theta < \gamma$	N	$X_{ri} = -\cos^2\alpha_s\left[\dfrac{r_i \tan\alpha_s}{\cos\alpha_s} - dM\tan\alpha - \left(\dfrac{2r_i dM}{\cos\alpha_s} d^2M^2\right)^{1/2}\right]$ $M = \sin\gamma_s + \tan\alpha_s \cos\gamma_s$	(16b*)
F	O	N	$\theta \geqslant \alpha$	$X_{ri} = -\cos^2\alpha_s\left[\dfrac{-r_i \tan\alpha_s}{\cos\alpha_s} + dM\tan\alpha - \left(\dfrac{2r_i dM}{\cos\alpha_s} - d^2M^2\right)^{1/2}\right]$ $M = \sin\gamma_s - \tan\alpha_s \cos\gamma_s$	(16c*)
F	O	N	$\theta < \alpha$	as (16b*)	
B	C	N	N	$X_{ri} = -\cos^2\alpha_s\left[\dfrac{r_i \tan\alpha_s}{\cos\alpha_s} + dM\tan\alpha - \left(\dfrac{-2r_i dM}{\cos\alpha_s} - d^2M^2\right)^{1/2}\right]$ $M = -\sin\gamma_s - \tan\alpha_s \cos\gamma_s$	(16d*)
B	O	$\theta \geqslant \gamma$	$\theta \geqslant \alpha$	$X_{ri} = -\cos^2\alpha_s\left[\dfrac{-r_i \tan\alpha_s}{\cos\alpha_s} - dM\tan\alpha - \left(\dfrac{-2r_i dM}{\cos\alpha_s} - d^2M^2\right)^{1/2}\right]$ $M = -\sin\gamma_s + \tan\alpha_s \cos\gamma_s$	(16e*)
B	O	$\theta < \gamma$	$\theta \geqslant \alpha$	$X_{ri} = -\cos^2\alpha_s\left[\dfrac{-r_i \tan\alpha_s}{\cos\alpha_s} - dM\tan\alpha - \left(\dfrac{-2r_i dM}{\cos\alpha} - d^2M^2\right)^{1/2}\right]$ $M = \sin\gamma_s + \tan\alpha_s \cos\gamma_s$	(16f*)
B	O	$\theta < \gamma$	$\theta < \gamma$	as (16d*)	
B	O	$\theta \geqslant \gamma$	$\theta < \alpha$	$X_{ri} = -\cos^2\alpha_s\left[\dfrac{-r_i \tan\alpha_s}{\cos\alpha_s} + dM\tan\alpha - \left(\dfrac{-2r_i dM}{\cos\alpha_s} - d^2M^2\right)^{1/2}\right]$ $M = -\sin\gamma_s - \tan\alpha_s \cos\gamma_s$	(16g*)

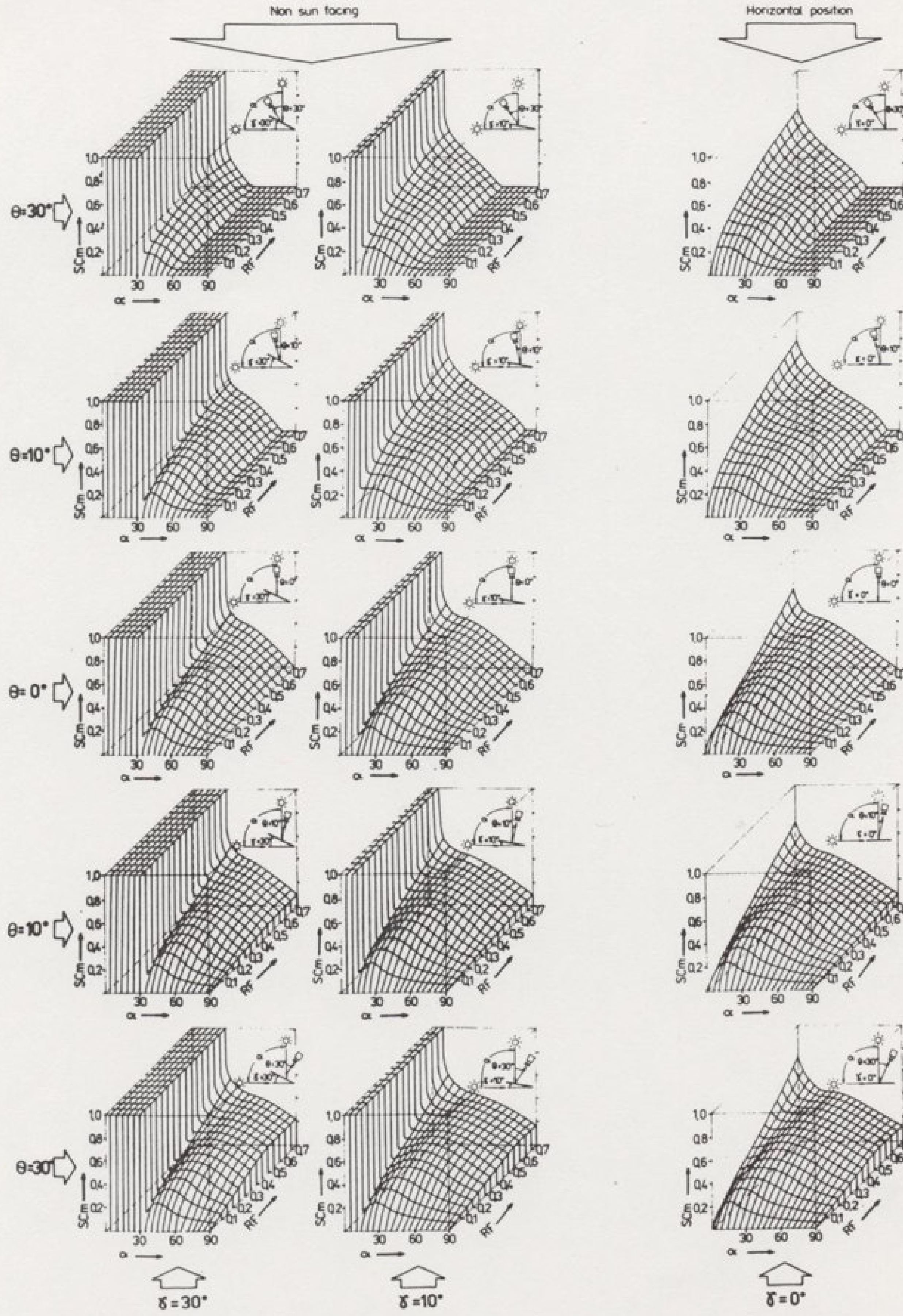

Figure 4. Relationship between the simulated shadowing coefficient of soil surface (SC_m) and the rough soil surface factor (RF_m), the solar altitude (α), the slope angle of soil surface (γ), and the zenithal observation angle (θ).

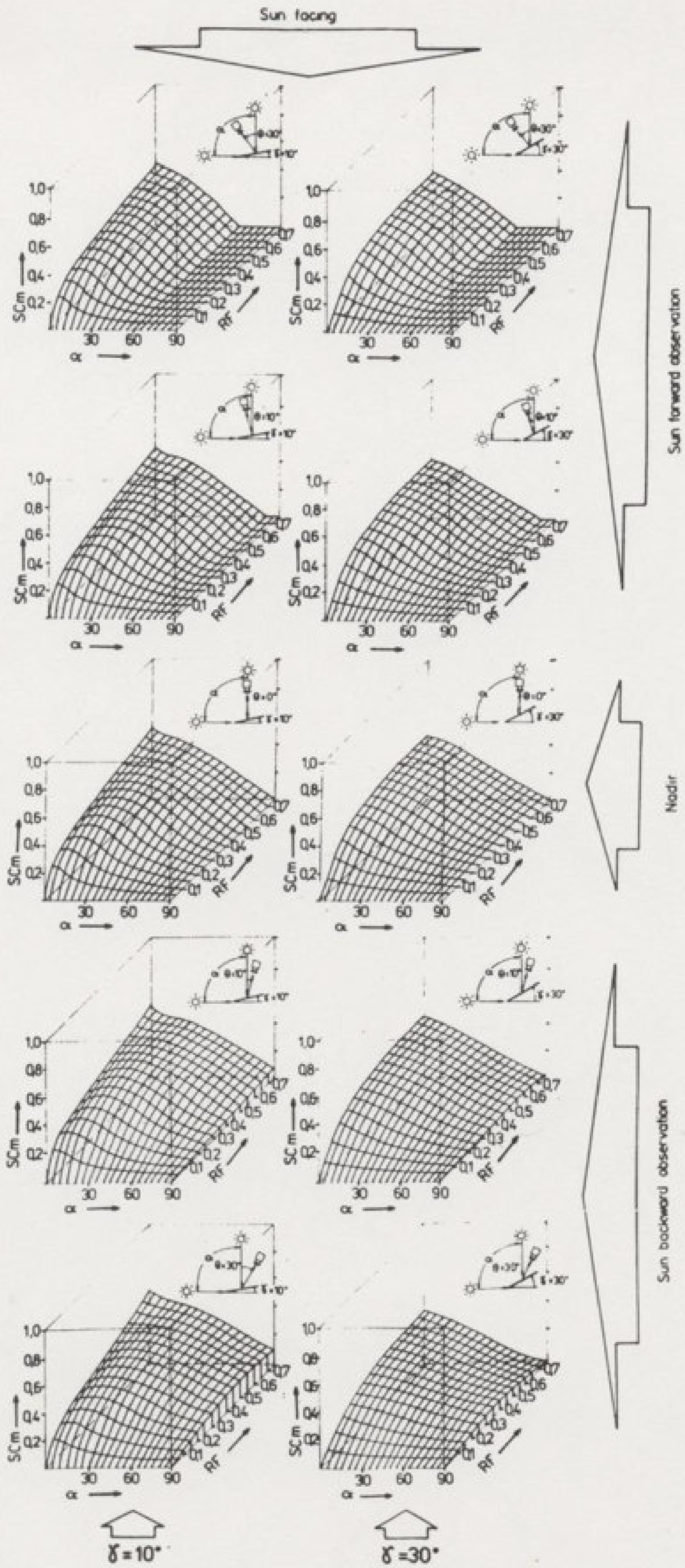

Figure 4. (*continued*)

Table 7. Soil Shadowing Coefficient (SC_m) for Different Illumination and Observation Conditions on the Example of Soil Surface Example with the Roughness Factor $RF_m = 0.3$

Solar Altitude (α^0)	Forward Observation $\theta = 30°$	Forward Observation $\theta = 10°$	Nadir $\theta = 0°$	Backward Observation $\theta = 10°$	Backward Observation $\theta = 30°$
		Forward (Sun-Facing) Slope $\gamma = 30°$			
15	0.28	0.33	0.34	0.33	0.29
30	0.15	0.23	0.26	0.27	0.24
45	0.06	0.13	0.16	0.19	0.2
60	0	0.06	0.09	0.12	0.15
75	0	0.01	0.04	0.07	0.11
90	0	0	0.02	0.02	0.06
		Horizontal Position $\gamma = 0°$			
15	0.35	0.4	0.37	0.37	0.36
30	0.28	0.35	0.36	0.38	0.38
45	0.16	0.29	0.28	0.31	0.34
60	0	0.16	0.15	0.2	0.26
75	0	0.03	0.06	0.1	0.17
90	0	0	0	0.03	0.09
		Backward (Non-Sun-Facing) Slope $\gamma = 30°$			
15	1	1	1	1	1
30	1	1	1	1	1
45	0.19	0.29	0.32	0.34	0.37
60	0	0.19	0.25	0.3	0.36
75	0	0.04	0.11	0.18	0.28
90	0	0	0.05	0.05	0.15

altitude (α) under which the shadowing parameter (SC_m) reaches 0:

$$\alpha_{SC_m = 0} \geqslant 90 - \theta. \quad (2)$$

The formula states that for observation from the nadir SC_m does not reach 0 before the sun zenith position.

Rough soil surfaces observed from a backward direction to sunbeams are more shadowed than those observed from the nadir and a lot more shadowed than those seen from a forward direction. When looking at the rough soil from the backward direction, its shadowing coefficient (SC_m) increases with an increase of the zenith observation angle (θ), whereas when looking at the same soil, but from the forward direction, this relation is opposite.

The SC_m coefficient differentiation resulting from the influence of the soil observation direction, analyzed on the example of a soil surface of average roughness for cultivated soils (Table 7), is clear. This influence is greater at a higher solar altitude, especially for the sun level (α) which satisfies the equation

$$\alpha \geqslant 90 - \theta. \quad (3)$$

The shadowing coefficient of soil surface (SC_m) for the zenith observation angle of 30° can even differ by more than 100% from the SC_m value in relation to the observation from the nadir direction.

The equations presented in this paper, describing the influence of observation conditions on the shadowing of soil surfaces observed by a sensor, not only can find application in the remote sensing of soils in the visible and near-infrared range of the spectrum, but also may be useful in the microwave range.

REFERENCE

Cierniewski, J. (1987), A model for soil surface roughness influence on the spectral response of bare soils in the visible and near-infrared range, *Remote Sens. Environ.* 23:97–115.