

Virtual surfaces simulating the bidirectional reflectance of semi-arid soils

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Abstract. Virtual surfaces of four semi-arid soils (regs, crusts, playas and sands), used to predict their bidirectional reflectance in the optical domain, are discussed in the paper. These surfaces are defined by the horizontal and vertical semi-axes of equal-sized opaque spheroids simulating their particles or aggregates. The spheroids are regularly dispersed in a net of squares of a given side length, on a freely sloping plane. They are absorbed into the ground with their tops projecting to a given height above the slope. The material of the vertical structure is additionally defined by its refractive index. Virtual surfaces determined in this way were used as part of the input data to a geometrical model, which predicts the soil surface normalized reflectance NR, expressed as the ratio of the total radiance of the simulated surface viewed from the off-nadir direction to the radiance viewed from the nadir.

1. Introduction

Information about interpreted objects recorded in remote sensing images in the optical domain is transmitted by electromagnetic radiation reflected from the surface of the objects. Bare soils, like many natural objects, show variation in their radiance due to the direction of irradiating solar energy and the direction along which the reflected energy is viewed by ground-based, airborne and satellite sensors. Soil surface irregularities, caused by the soil texture, aggregates and micro-relief configuration, which are large compared with the wavelengths, and that are opaque, cast shadows on the surfaces. The variation caused by the shadows when viewed by the sensors is the basic reason for the soil bidirectional reflectance behaviour, because the wave energy leaving the shaded areas is many orders of magnitude smaller than the energy reflected from the sunlit soil fragments.

Cultivated soils with dominant diffuse features usually seem to be brightest when sensed from the direction that gives the lowest proportion of shaded fragments.

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Those soil surfaces usually display a clear backscattering character with a reflectance peak towards the Sun position and decreasing reflectance in the direction away from the peak. Laboratory results presented by Coulson (1966) show that desert soil materials like gypsum sand and beach quartz sand display a high reflectance and a strong forwardscatter maximum for wavelengths in the visible and near-infrared range. The directional reflectance of these soil surfaces clearly varies with the angle of the incident radiation. The backscatter, as well as the forwardscatter, regimes in soil reflectance in the optical domain have been identified by Deering et al. (1990). They have been demonstrated with examples from an alkali flat bare soil and dune sand surface. The first surface, which comprised a coarse texture and bright-stabilized crust with intermittent darker patches, displayed the distribution pattern of strong backscatter reflectance. The second surface, composed of nearly pure gypsum crystals creating uniform wind ripples, showed forwardscatter as its predominant feature. The sharp peak in the forward direction manifests a considerable contribution of the specular component to total reflectance from these fine gypsum sand grains, derived from selenite flakes. Shoshany (1993), collecting more than 70 datasets for different types of desert stone pavements and rocky surfaces in Australia under varied illumination conditions, found that most of the surfaces exhibited an anisotropic reflection with a clear backscattering component. Eaton and Dirmhin (1979) observed that predominant forwardscatter also characterized natural surfaces like snow and salt flats. Most geometrical soil directional reflectance models that have been proposed predict soil reflectance based on the assumption that shadowing from soil irregularities has a greater influence than the scattering properties of a soil material at the micro-scale. Walthall et al. (1985) express bidirectional reflectance of a bare soil surface as a three-parameter function of view direction to the solar direction. These parameters of an empirical character are not explicitly related to soil surface properties. The function cannot be used to predict soil reflectance distribution for soil surfaces other than those analysed. Soil aggregates in the model of Norman et al. (1985) were simulated with cuboids. The bidirectional reflectance distribution function for the simulated soil surface shows a clear backscatter regime. The height of soil surfaces in the Monte Carlo reflectance model of Cooper and Smith (1985) varied periodically with the cosine function in one or two directions. It assumes that the soil is a perfectly diffuse reflector at the microscopic level, such that the probability that a photon will be scattered at a given angle only depends on the orientation of the soil surface irregularities. The diffuse character of the model also shows a backscattering regime of the soil directional reflectance. The models of Hapke (1981, 1984, 1986), developed for the interpretation of reflectance properties of planetary surfaces, produce bidirectional signatures like those of a medium composed of particles characterized by a single-scattering albedo and a phase function. The models take into account a parameter that depends upon regolith porosity and particle size distribution. The models, as used by Pinty et al. (1989), have five input parameters: a single scattering coefficient, two parameters describing the hot spot phenomenon, and two parameters describing the scattering phase function. Jacquemoud et al. (1992) added to Hapke's model a specular contribution and separated those parameters that depend on wavelength from those which are not wavelength-dependent. The model of Irons et al. (1992) describes a soil surface consisting of uniform opaque spheres regularly spaced on a horizontal surface. The geometry of the structure is defined as the area of a single sphere in its horizontal projection in a circle of unit area of the horizontal surface. Both direct and

isotropically diffuse light illuminate the soil surface. The spheres and background are Lambertian. Soil reflectance is expressed as a function of the horizontal area shaded by the spheres, the sunlit fraction, and the proportion of diffuse illumination. The model of Otterman (Otterman 1981, Otterman and Tucker 1985, Deering et al. 1990) treats bare soils as composed of thin vertical cylinders of variable heights with facet-reflectance and transmittance located randomly on a horizontal plane with Lambertian reflectance. The architecture of the soil protrusions is described by a parameter that is the sum of the height times the diameter of these cylinders per unit horizontal area. The model assumes that the facet-reflectance largely controls the backscatter while facet transmittance is responsible for determining forward scattering. This was the first model simulating both backscattering and forward scattering. It predicted a clear forward scattering character of reflectance for a surface with nearly pure gypsum crystals of high transmittance. The models of Cierniewski (1987, 1989) describe soil aggregates by regularly spaced equal-sized opaque spheres, while the models of Cierniewski and Verbrugghe's (1994) simulate them by spheroids of a defined proportion of their vertical to horizontal radii. All the models assume only perfectly diffuse reflection from the sunlit soil fragments. Improved versions of the models, describing bidirectional reflectance from non-directional rough soil surface with regular dispersed soil aggregates, also take into account specular features of the soil material (Cierniewski et al. 1996, Cierniewski and Verbrugghe 1997). The models assume that the energy leaving a given sunlit facet of the geometrical structures has a specular-diffuse character. A part of the direct energy is reflected as from a near-perfectly specular object and the other part as from a perfectly diffuse one. The first model describes the distribution of the energy leaving soil surfaces by the empirical function, while the second one uses the Fresnel equations treating reflected light as unpolarized. The reflectance of the simulated soil surface is finally expressed by the normalized reflectance factor, defined as the proportion of the total radiance measured from the off-nadir direction to the radiance measured from the nadir.

A new model, developed by Cierniewski (1999), simulates soil particles or aggregates as opaque spheroids. They are spatially regularly dispersed and partially buried in the ground of the plane on which they are distributed. The simulated surface is illuminated by the direct solar beam as well as di^{ff}use light. The model assumes that the electromagnetic energy leaves the surface in both the di^{ff}use and the specular ways.

The aim of this paper is to apply the above model to four arid soil surfaces that differ by texture and roughness. Their virtual surfaces were used for predicting the soil bidirectional reflectance.

2. Methodology

2.1. The study area

This research was conducted in a sand dune environment located in the northwestern Negev desert (Israel) near the border between Israel and Egypt. The region is semi-arid with 100 mm of mean annual rainfall, concentrated during the winter months (October to April). The area is characterized by sparse higher vegetation cover. The perennials cover about 14% of the area, annuals vary from null during the dry seasons to about 27% in the spring when they exhibit peak biomass. Consequentially, from the remote sensing point of few, it is quite obvious that the soil background is the dominant feature that contributes to the overall spectral response of the region.

Due to limited human and animal activities in the Negev, most of the region consists of stabilized linear dunes (Karnieli and Tsoar 1995). Four morphological units of various texture compositions as well as different surface roughnesses exist in the study area: regs, crusts, playas and sands. These units were selected to be the objects of our research:

Regs (figure 1(a)): at the edges of the dune area there are isolated patches, a few hundred square meters in area, of reg soils, which are also denoted as desert pavement. Gravel and flint fragments (a few centimetres in diameter) that are a product of in situ weathering cover these surfaces. The patches contain very little soil (mostly fines) that occurs in the interstices between the stones of the pavement, thus the stones are partially submerged beneath the surface and partially above (Evenari et al. 1982).

Crusts (figure 1(b)): the basal dune and interdune corridors extend over some 85% of the area. The surface is covered by a rather contiguous biogenic soil crust consisting mainly of cyanobacteria where Microcoleus vaginatus is the dominant species accompanied by Scytonema, Schizothrix, Calothrix, Chroococcidiopsis, Nostoc and Phormidium (Danin et al. 1989, Danin 1991, Karnieli 1997). During the dry periods, the cyanobacteria are located just beneath the soil surface. This crust of a few millimetres depth glues the soil particles together, mainly fines (silt and clay, up to about 40%) and has a relatively high organic matter content (1-2%). Therefore, biological soil crusts play a major role in dune stabilization. The micro relief of the biogenic soil crusts is relatively rough and characterized by many small depressions.







(c)

Figure 1. Close-up view of the soil surfaces: (a) reg; (b) crust; (c) playa; and (d) sand.

Playas (figure 1(c)): also in the interdune corridors exist the playa surfaces that are flat whitish isolated patches of up to a few hundreds of square metres in area. These playas are relics of an old flood plain consisting of up to 70% fines and almost do not contain any microphytic communities. Therefore, the playa crusts are considered as a physical crust. When dry, they form polygons of cracks of different shapes, each of a few hundreds of squared centimetres. The playa surface is very smooth.

Sands (figure 1(d)): the dune crests sited at the upper part of the sand ridge cover some 10% of the area. They are composed of about 98% unconsolidated active sand. The organic matter content is very low (0.1%). Although the surface is relatively smooth, the wind causes uniform ripple features on top of the sand formation.

2.2. Measurements

Four datasets were acquired for each ground unit in August 1996 and June 1999 during several days of measurements. Ground radiometric measurement was done with a CIMEL 313-21 radiometer at 10° sensor field of view (FOV). This instrument measures luminance in four different wavelengths: 550, 650, 850 and 1650 nm. The sensor was held at 2.5 m above the surface by attaching it to a bidirectional reflectance apparatus, resulting in a 43.7 cm diameter sample view area, at nadir. The apparatus was rotated according to the solar principal plane. Each sequence, lasting about 6 min, contains measurements from -70° (forward, toward the Sun) to $+70^{\circ}$ (backward, away from the Sun) in 10° increments. Nadir measurements were conducted at the beginning and at the end of each sequence (total of 17 measurements in each sequence). The apparatus was moved from one unit to another during the day, from sunrise to sunset, thus we obtained between 5 and 11 sequences of data for each unit.

Ground roughness was measured with a special device called BGUGSS 1800, invented by the Geography Department of Ben Gurion University of the Negev. This laser-based equipment, mounted on a tripod about 1.8 m above the ground, measures the surface roughness in an area of $87 \text{ cm} \times 87 \text{ cm}$ of the ground beneath. The vertical accuracy of this instrument is 1.5 mm and the spatial resolution is 1 cm.

The roughness state of these surfaces was quantitatively assessed with a roughness index RI, which expresses the average height deviation between each pixel x^i of a given surface and the eight closest pixels surrounding it x^s , averaged for the entire measured area with the following equation:

$$RI = \frac{\sum_{i=1}^{m_p} \left(\sum_{j=1}^{n_p} |x_i - (x_s)_j| \right) / n_p}{m_p - 4(\sqrt{m_p} - 1)}$$
(1)

where n_P and m_P denote the number of pixels in each moving window and the total number of pixels of given surface which are 8 and $87^2 = 7569$, respectively.

2.3. The model

The virtual soil surfaces were originally used as part of the input data for modelling the distribution of electromagnetic radiation in the optical domain reflected from a rough soil surface. The roughness is caused by irregularities of soil particles or aggregates dispersed regularly in all directions.

Equal-sized opaque spheroids of horizontal, a, and vertical, b, radii lying on a plane sloping at angle ε , simulate the soil surface (figure 2). They are absorbed into



Figure 2. Schematic representation of the model geometry.

the ground of the slope plane, with their tops projecting at height t above the ground. These spheroids are regularly arranged on the slope plane such that their centres are in a square grid of interval d. The resulting geometrical surface structure is illuminated by direct solar beams at zenith angle θ_s as well as diffuse light. A sensor is suspended over the simulated soil surface for observing it along the solar principal plane *SPP* at zenith angles θ_v , with $\Delta \theta_v$ increments in the forwardscattering and backscattering directions, represented by negative and positive values of the θ_v , respectively. The sensor defines the angle α with its field of view and is located at a distance of h away from the observed point.

In the first step of the calculation for a given profile, the position of all the border points between the directly illuminated and shaded fragments of the geometrical structure is computed. The amount of the radiative energy coming directly to the illuminated individual facet fa of the geometrical structure, the ellipse, and the soil slope between the ellipses, defines the factor Eiv_{fa}^{α} :

$$Eiv \,{}^{\alpha}_{fa} = \cos\theta_s \cos\beta + \sin\beta + \sin\theta_s \cos(\phi_r - \phi_s) \tag{2}$$

where β is the slope angle of the facet, and ϕ_r and ϕ_s are the azimuth angles describing the positions of the facet and the Sun, respectively. The value of this factor $Eiv \, f_a$, equals the cosine of the incidence angle γ of the direct solar beams to the facet, measured with respect to its normal. It expresses the vector length of the energy leaving the facet along the normal. The energy leaving the directly illuminated facets $Eiv^{\dagger}f_a$ is directly proportional to the energy incident on it $Eiv^{\dagger}f_a$. The $Eiv^{\dagger}f_a$ is in part perfectly diffused, and in part reflected in a specular way. The model assumes that the length of the reflected energy vector in a given direction θ_v is the sum of the lengths of these two vectors (i.e. the perfectly diffused energy $Edi(\theta_v)^{\uparrow} f^a$ and the energy specularly reflected $Esp_{\theta v}^{\uparrow} f^a$ (figure 3)):

$$Ei_{\theta\nu}{}^{\uparrow}fa = Edi_{\theta\nu}{}^{\uparrow}fa + Esp_{\theta\nu}{}^{\uparrow}fa \tag{3}$$

The length of the vector $Esp_{\theta v}^{\uparrow} f_a$ describing unpolarized light, depends on the polarization $Fp(\gamma)$ of the reflected light $Eiv^{\circ} f_a$ at angle γi , as follows:

$$Esp_{\theta v}^{\uparrow} fa = Eiv^{\uparrow} fa. Fp(y); Fp(y) = \frac{r_{\perp}^{2} + r_{=}^{2}}{2}$$
(4)

where $r\perp$ and r= are, respectively, the perpendicular and parallel Fresnel reflection coefficients, given by:

$$r_{\perp} = \frac{-n^{2} \cos \gamma i + \sqrt{n^{2} - \sin^{2} \gamma i}}{n^{2} \cos \gamma i + \sqrt{n^{2} - \sin^{2} \gamma i}}; r_{=} = \frac{\cos \gamma i - \sqrt{n^{2} - \sin^{2} \gamma i}}{\cos \gamma i + \sqrt{n^{2} - \sin^{2} \gamma i}}$$

where *n* is the refractive index of the soil surface. The vector of the energy specularly reflected is oriented in such a way that the angle of incidence, γ^i , equals the angle of reflection, γ^r . As the vector of the quasi-specular reflected energy, it is visible inside the limited angle range defined by the angle 2∂ around the direction of reflection $\gamma^r \pm \partial$, where $\gamma^r = \theta s - 2\gamma^i$. The model assumes that the length of the vector $Esp_{\theta v} {}^{\uparrow} f^a$ decreases to zero linearly from this direction γ^r to the range limit.



Figure 3. Distribution of the energy leaving a facet of a simulated soil surface in the specular and diffuse modes.

The length of the vector $Ei_{\theta v}^{\uparrow} f_a$ completes the diffuse component $Edi_{\theta v}^{\uparrow} f_a$ defined as:

$$E di_{\theta v}{}^{\mathsf{T}} f a = (1 - F p(\gamma i)) E i v {}^{\mathsf{T}} f a \cos \theta v$$
(5)

Finally, the total energy $Eis_{\theta\nu} f_a$ leaving a given directly illuminated facet fa and reaching the sensor oriented at an angle $\theta\nu$ is sensed as the amount $Ei_{\theta\nu} f_a$ divided by the cosine $\theta\nu$.

The diffuse light $Esk f_a$ reaches the soil surface fragments directly illuminated by the sun beams, as well as the shaded fragments. Its amount is limited by the presence of adjoining spheroids (ellipses in profiles), which reduce the amount of diffuse energy relative to the condition when it comes from the complete hemisphere. As a result, the additional portion of the energy dispersed from a given facet is described as follows (figure 4):

$$Esk_{fa}^{\uparrow} = f_{di} \frac{\delta}{180^{\circ}} \tag{6}$$

where f^{di} approximates a reflectance effect from soil surfaces illuminated only by the diffuse light component and is defined as part of the direct solar beam's energy.



Figure 4. Limitations in illumination by skylight of the facet segment LR on the ellipse E_1 and the slope plane between ellipses E_1 and E_2 , expressed by the angle δ . M is the middle point of the segments LR and G_1G_2 . T, T_1 and T_2 are the tangent points from the sides to the neighbouring ellipses forming the angle δ .

The radiance factor of the simulated soil surface, with directly illuminated and shaded fragments, viewed by the sensor from a given direction θ_v along a given profile *pr*, is defined as:

$$L_{\theta v}^{\uparrow} {}_{pr} = \sum_{i=1}^{j} \{ (Eis_{\theta v}^{\uparrow} f_{a(i)} + Esk_{a(i)}^{\uparrow})\xi_{i}f_{a(i)} \} + \sum_{i=1}^{j} (Esk_{a(i)}^{\uparrow}\xi_{s}f_{a(i)})$$
(7)

where *i* is the *i*th facet of the geometrical structure, $\xi i f_{a(i)}$ and $\xi s f_{a(i)}$ are the elementary view angles of the illuminated and the shaded *i*th facet, respectively. The radiance of the simulated soil surface reaching the sensor through its field of view $L_{\theta v}^{\uparrow} FOV$ is the sum of the values calculated along the individual profiles $L_{\theta v}^{\uparrow} pr$ and the space between the spheroids.

Finally, the reflectance from a rough soil surface along the solar principal plane *SPP* is described by the normalized reflectance $NR(\phi_v = SPP, \theta_v)$, which is defined as the ratio of the total radiance $L_{\theta_v}^{\uparrow}$ Fov measured from the off-nadir direction θ_v to the radiance measured from the nadir. Assuming that the normalized surface reflectance $NR(\phi_v = SPP, \theta_v)$ in the plane *OP* perpendicularly oriented to the *SPP* for each of the view zenith angles θ_v is 1 and the ratio in the function of the ϕ_v between the *SPP* and the *OP* has a simple linear distribution, its value $NR(\phi_v, \theta_v)$ for any observation plane can be defined as:

$$NR_{(\phi_v,\theta_v)} = NR_{(\phi_v = SPP,\theta_v)} \left(1 - \frac{\phi_v}{90^\circ}\right) + \frac{\phi_v}{90^\circ}$$
(8)

where ϕ_{ν} is the relative horizontal angle of the observation plane measured from the *SPP*. The model is applicable, when the observation plane goes along the direction of the highest sloping line of a simulated surface. The model, presented above was prepared in the form of a computer program, written in Pascal.

2.4. Fitting of the virtual surface geometry

The geometry of the virtual surfaces discussed in the paper was obtained by the inversion of the model described in this work. The fitting of the geometrical parameters to the soil reflectance measurements involves choosing those values of the input parameters, which give us the lowest possible root mean square error *rms* between the modelling and the measured distribution of the normalized surface reflectance *NR* as a function of view zenith angle. These parameters include the spheroid vertical radius *b*, the distances between the spheroids *d*, the height of spheroid tops above the ground *t*, completed by the refractive index of the soil surface *n*, and the ratio of the reflected diffuse light *f*^{*di*} for a given wavelength. The horizontal radius of the spheroids *a*, was evaluated as its average value for a given surface. Other parameters describing conditions of illumination and observation of the studied soil surfaces, θ_s , *h*, α , were taken as their measured values.

This fitting was performed automatically using a special computer procedure. A program, written in Object Pascal, automatically fits the geometrical parameters of the analysed soil surfaces. It is realized in two stages. In the first one, for a surface at each solar zenith angle θ_s , the program computes the $rms_{\theta_s,s}$ using the following formula:

$$rms_{\theta s,s} = \frac{1}{nv-1} \sqrt{\sum_{nv-1}^{nv} (M_{\theta s,\theta v} - P_{\theta s,\theta v,s})^2}$$
(9)

where nv is the number of θ^v , $M_{\theta s, \theta v}$ is a measured value of the NR for given angles θ^s and θ^v , $P_{\theta s, \theta v, s}$ is a predicted value of NR for these two angles and the set s of parameters: b, t, d, n and f_{di} . All data collected when the luminance meter cast a shadow on the observed surface were eliminated from the calculation. In the second stage the program determines the quantities K_s :

$$K_s = \sum rm_{S\theta_s,s} \tag{10}$$

where the sum is spread over all values of θ_s . Finally, the minimum value among the computed K_s 's is found and it indicates the set s for which the average root mean square is the lowest.

3. Results and discussion

3.1. Roughness of soil surfaces

The roughness of the four soil surfaces that are analysed in the paper are illustrated in figures 5(a)-(d). The lowest roughness corresponds to the playa surface (figure 5(c)), whose height variation does not exceed 10 mm. The height irregularities are a consequence of cracks on the surface between the physical crust polygons. Similarly, the dune sand surface shows low roughness characteristics (figure 5(d)). Its maximum height variation reaching 15 mm is the effect of ripple marks. The biological crust (figure 5(b)) creates a clearly irregular plane with maximum irregularities of about 20 mm that are randomly spread over the surface. The highest roughness is exhibited by the reg surface (figure 5(a)). Flint fragments lying on this surface generate irregularities often exceeding 70 mm in height. Roughness index *RI* (equation (1)) values of 1.22, 1.53, 3.24 and 7.39 mm were obtained for the playa, sand, crust and reg surfaces, respectively.

3.2. Virtual soil surfaces

The following assumptions were made while fitting the parameters of these virtual surfaces:

- All the parameters describing the geometry of a studied surface (a, b, t and d) at a given roughness state are independent of the illumination and viewing conditions; their values were fitted with a precision of 0.005 cm, except those describing the reg surface, which were fitted with the precision of 0.1 cm.
- For a given wavelength, the refractive index n of a soil surface, as well as the reflected diffuse light f^{di} , is independent of the solar zenith angle θ_s ; their values were fitted with a precision of 0.05.

All the model-generated data were obtained with the ratio of the di^{ff}use light of 0.05 independent of wavelength, assuming that a higher proportion of the di^{ff}use light in the energy illuminating the target at lower wavelengths is compensated by its corresponding higher absorption at lower wavelengths after reflection. It was also assumed that the vectors of the quasi-specular component of the reflected energy were visible around the direction of reflection whose angular distance ∂ equals 30°. This was practically fixed as the best value for the normalized reflectance curves for all the analysed soil materials (figure 6). The model executed the calculation of the soil directional reflectance along the five 2-D profiles, dividing into three segments



Figure 5. Soil surface roughness as obtained from the BGUGSS equipment data: (a) reg; (b) crust; (c) playa; and (d) sand.

each curve-linear fragment of a soil geometrical structure viewed by the sensor as an individual category of the directly illuminated and shaded soil surface.

The values of all of these virtual surface parameters fitted by the inversion of the model are listed in table 1 and presented in figure $7^{(a)-(d)}$. The sizes of these virtual surfaces have been linearly enlarged with respect to their real equivalents on the ground. The enlargement factors are $0.25 \text{ cm} \times 0.25 \text{ cm}$ for the playa and the sand, $2.5 \text{ cm} \times 2.5 \text{ cm}$ for the crust, and $25 \text{ cm} \times 25 \text{ cm}$ for the reg. All the surfaces are presented in the same illumination and viewing conditions.

The virtual reg surface (figure 7(*a*)) is essentially different in terms of its size, its irregularities, and its shape compared to the other analysed surfaces. It is described by the spheroids with the highest vertical elongation (b/a=4). The virtual surface simulating the crust (figure 7(*b*)), like in nature, is rough as well. It is described by the spheroids touching each other with a vertical elongation b/a of 1.2 and a relatively small absorption into the plane of the ground, which is the lowest in relation to the other analysed surfaces (t/a=1). The playa material (figure 7(*c*)), essentially smoother and characterized by a finer texture, is simulated by spheroids 2.5 times lower in height than their horizontal radius *a* in relation to the spheroids of the remaining surfaces. The virtual playa's spheroids are the most flattened (b/a=0.8). They are absorbed deepest into the ground and arranged with larger distances between them than the crust's spheroids. Probably, the cracks on the dried playa material prevent its virtual surface from being the smoothest among the analysed surfaces, even



Figure 6. Relation between the normalized reflectance NR of the analysed soil surfaces along the solar principal plane for the 850 nm channel predicted by the model (solid line) and measured (dashed line) for selected solar zenith angles θ_s .

though its texture may indicate so. The sand surface (figure 7(d)) represents the smoothest virtual surface. Although it is described by less vertically elongated spheroids (b/a = 1.1), these are the deepest absorbed into the ground (t/a = 0.7) and have the highest proportion of flat spaces between their emerged fragments compared to the other surfaces.

One geometrical parameter of these virtual surfaces corresponds to real shape of



Figure 6. (Continued).

the studied surfaces. It is the horizontal radius of the spheroids a, which in accordance with the assumption of the virtual surfaces fitting equals in approximation the average radius of irregularities of these surfaces. It causes that general shape of these studied surfaces and their virtual equivalents is rather similar. In this initial stage of the studies a quantitative relation between the roughness state of the real surfaces, described by their roughness index RI, and a similar roughness parameter of the virtual surfaces was not found.

					n			
Surface	<i>a</i> (cm)	b/a	t/a	d/a	550 nm	650 nm	850 nm	1650 nm
Reg	1.000	4.0	0.7	1.75	2.6	2.5	2.3	2.3
Crust	0.250	1.2	1.0	2.00	2.9	2.5	2.3	2.3
Playa Sand	0.010 0.025	0.8 1.1	0.9 0.7	2.15 2.00	2.1 2.2	2.0 2.0	1.9 1.9	1.9 1.8

Table 1. Geometry and the refractive index n of the virtual surfaces.



Figure 7. The virtual equivalents of the soil surfaces: (a) reg 25×25 cm; (b) crust 2.5×2.5 cm; (c) playa 0.25×0.25 cm; and (d) sand 0.25×0.25 cm.

3.3. The normalized reflectance curves

The high proportion of flat spaces between the spheroids and the spheroids themselves (with almost spherical cross-sections and relatively flat tops) for the sand virtual surface produced the lowest variation of its normalized reflectance NR in the entire range of the view zenith angle function along the solar principal plane SPP for solar zenith angles θ_s lower than 40° (figure 6). For θ_s higher than 40° its NR variation clearly grows in the forwardscattering directions as a consequence of its specular effects, the most intensive among the four analysed soil surface types. The flatness of the playa's virtual surface spheroids has caused its NR curves to resemble those of the sand surface more than those of the crust. The virtual surface representing the crust, whose high roughness is caused mainly by the small absorption of the virtually elongated spheroids into the ground, yielded NR curves with essentially less visible specular effects in the forward scattering range. However, this curve shows the highest variation of the normalized reflectance in the backscattering range. The shapes of the NR curves for the crust are very similar to those of the reg, especially in the backscattering range. The reg NR curves demonstrate specular effects weakly in the forward scattering range.

Measured and model-generated NR curves related to the near-infrared channel (850 nm) in figure 6 show good mutual fitting. The goodness of fit depends on

wavelength (table 2). For all the analysed soil surfaces the fitting accuracy for the green light (550 nm) is the lowest. It is clearly higher for the red light (650 nm) and highest for the near-infrared (850 nm), as well as for the middle-infrared (1650 nm).

3.4. Spectral contrast between the analysed surfaces

The high fitting accuracy between the measured and the model generated data enables us to predict the reflectance behaviour of the analysed soil surfaces under any illumination and observation conditions using their virtual surfaces. Figure 8 shows the distribution of the reflectance R of these soil surfaces at 850 nm as a function of the view zenith angle for some chosen solar zenith angles along the solar principal plane, where R variation is the highest. Use of the R, which expresses the proportion of soil radiance to the radiance of a standard reflectivity panel, also enables us to take into account the difference in brightness between the analysed soil materials. These curves were obtained from the individual soil NR curves by multiplying their NR data by the ratio of a given soil radiance to the radiance of the standard panel, both collected at nadir at the same solar zenith angle. Reflectance curves generated in this way make it possible to predict in which illumination and viewing conditions the spectral contrast between analysed surfaces is highest. These curves show that viewing these surfaces from the nadir makes it relatively di^{ffi}cult to separate the sand from the playa and the crust from the reg. It is clearly easier

			rms					
Surface	heta s	550 nm	650 nm	850 nm	1650 nm			
Reg	20.5	0.028	0.027	0.021	0.022			
	30.4	0.038	0.034	0.028	0.025			
	33.8	0.029	0.024	0.019	0.015			
	53.1	0.024	0.018	0.013	0.016			
	61.4	0.019	0.025	0.020	0.024			
	Average	0.028	0.026	0.020	0.020			
Crust	20.9	0.030	0.023	0.018	0.015			
	28.4	0.022	0.019	0.016	0.016			
	33.9	0.025	0.018	0.015	0.015			
	51.1	0.013	0.016	0.020	0.024			
	65.9	0.018	0.024	0.016	0.021			
	Average	0.022	0.022	0.017	0.018			
Playa	20.8	0.022	0.017	0.015	0.014			
-	29.4	0.016	0.010	0.012	0.008			
	31.9	0.022	0.015	0.012	0.012			
	47.3	0.017	0.010	0.014	0.017			
	62.3	0.014	0.017	0.014	0.020			
	Average	0.018	0.014	0.013	0.014			
Sand	21.1	0.025	0.017	0.010	0.010			
	28.4	0.025	0.017	0.012	0.012			
	35.1	0.035	0.021	0.018	0.012			
	53.5	0.025	0.018	0.014	0.017			
	63.0	0.012	0.010	0.013	0.020			
	Average	0.024	0.017	0.013	0.014			

 Table 2.
 Root mean square error rms for measured and predicted reflectance data generated by the model using the virtual surface parameters.

to separate them when they are observed obliquely. The contrast between the sand and the playa becomes higher if the sensor looks from the backscattering directions at view zenith angles higher than 20° and at solar zenith angles between 35° and 65° . However, the contrast between the crust and the reg rises if the sensor observes them from the forwardscattering directions, at zenith angles lower than -50° , and especially at extremely high solar zenith angles (e.g. 80°).

The examples discussed here enable us to understand better the interaction of electromagnetic radiation with soil surfaces under different geometric conditions. These virtual surfaces can be used for re-constructing the bidirectional reflectance factors of soil surfaces from a limited sample of angular reflectance measurements and to convert remote sensing data collected under different illumination and viewing conditions to standardized forms, which will contribute to improved interpretations. The procedure described in this paper offers a major contribution for different types of operational space systems: (1) wide field-of-view (FOV) sensors, such as NOAA AVHRR or SPOT 4 VEGETATION; (2) narrow FOV sensors tilted at different angles such as SPOT HRV, and (3) conical scanning sensors of the ERS-1 ATSR type. The potential of reflectance data recorded at several sensor view angles will increase with the launching in the near future of new instruments of NASA's Earth Observing System: the Moderate Resolution Imaging Spectrometer (MODIS) having an along-track viewing capability of up to $\pm 55^{\circ}$, and the Multi-angle Imaging SpectroRadiometer (MISR) acquiring multiple images of the Earth's surface at different sensor view angles in the range $\pm 58^{\circ}$ within a single orbital overpass (Barnsley 1994). Those virtual surfaces can also be applied to accurate estimates of the albedo of soil surfaces, a parameter of great importance in climate modelling.

4. Conclusions

The model presented in the paper, using the virtual soil surfaces (being a set of input data describing the geometry and reflectance features of each soil), has enabled us to predict the directional reflectance behaviour of semi-arid soil surfaces, namely: regs, crusts, playas and sands, in any illumination and viewing conditions. The geometry of these virtual surfaces has been described with spheroids of given horizontal and vertical radii lying on a freely sloping plane. They are absorbed into the ground of the slope plane with their tops projecting at a given height above the ground. The spheroids are regularly arranged in a square grid pattern on the slope.

The virtual surface of the reg is essentially di^{ff}erent from the other analysed surfaces in terms of the size of its irregularities and its shape. It is described by spheroids having vertical elongation 3.3–5 times higher than those representing the remaining surfaces, whose spheroids are almost spherical. The spheroids of the virtual surface simulating the crust, which clearly displays more roughness than the playa and the sand, are only slightly absorbed into the plane of the ground. The virtual playa's spheroids are flattened, while the spheroids of the sand's surface are a little vertically elongated. The spheroids of both surfaces are absorbed deeper into the ground and arranged with larger distances between them than the crust's spheroids.

The large proportion of flat spaces between the virtual spheroids and the relatively flat tops of the spheroids enabled us to generate with the model the soil normalized reflectance NR curves along the solar principal plane having a low variation of NR with view zenith angle. Flat fragments of soil virtual surfaces were also useful for generating the specular effects of the soil reflectance characteristic of smooth surfaces like the sand and the playa. The virtual surface simulating the crust, with the

vertically elongated spheroids slightly absorbed into the ground, shows essentially less obvious specular effects and a prominent variability of the NR in the backscattering directions. Similar NR curves were generated by the reg virtual surface, although their geometry is clearly different.

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