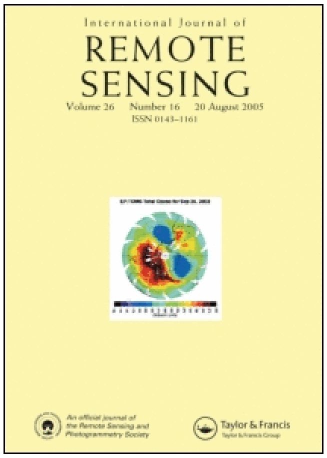

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Differentiation of semi-arid vegetation types based on multi-angular observations from MISR and MODIS

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Mapping accurately vegetation type is one of the main challenges for monitoring arid and semi-arid grasslands with remote sensing. The multi-angle approach has been demonstrated to be useful for mapping vegetation types in deserts. The current paper presents a study on the use of directional reflectance derived from two sensor systems, using two different models to analyse the data and two different classifiers as a means of mapping vegetation types. The multiangle imaging spectroradiometer (MISR) and the moderate resolution imaging spectroradiometer (MODIS) provide multi-spectral and angular, off-nadir observations. In this study, we demonstrate that reflectance from MISR observations and reflectance anisotropy patterns derived from MODIS observations are capable of working together to increase classification accuracy. The patterns are described by parameters of the modified Rahman–Pinty–Verstraete and the RossThin-LiSparseMODIS bidirectional reflectance distribution function (BRDF) models. The anisotropy patterns derived from MODIS observations are highly complementary to reflectance derived from radiances observed by MISR. Support vector machine algorithms exploit the information carried by the same data sets more effectively than the maximum likelihood classifier.

1. Introduction

Differentiation of semi-arid vegetation types is a classification problem (Kremer and Running 1993). It implies a large number of classes that differ more subtly than the broader categories assigned to regional or global classification schemes. The land surface scatters solar radiation anisotropically. Multiple view angle data could provide information on canopy structure and disturbance that is inaccessible using single view angle technologies. The factors derived from multiangle measurements have been suggested to be integrated into land cover classification activities (Abuelgasim *et al.* 1996, Pinty *et al.* 2002, Zhang *et al.* 2002, Su *et al.* 2005). The reflectance anisotropy patterns depend on the three-dimensional character and optical properties of the surface and can be used to characterize the surface target; it should be reasonable to introduce them as additional discriminatory variables into a classification procedure. The presemt study investigates the use of directional reflectance from two different sensor systems, two different models of the directional

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reflectance and two different classifiers as a means of mapping vegetation types in deserts. This study emphasizes a distinctive capability provided by combining these patterns derived from the moderate resolution imaging spectroradiometer (MODIS) observations and reflectance derived from the multiangle imaging spectroradiometer (MISR) observations for differentiation of semi-arid vegetation types.

The modified Rahman–Pinty–Verstraete (MRPV) model (Engelsen *et al.* 1996, Diner *et al.* 1999) and the RossThin-LiSparseMODIS (RTnLS) model (Wanner *et al.* 1995, Strahler and Muller 1999) were applied to invert bidirectional reflectance distribution function (BRDF) parameters from MISR and MODIS reflectance. The MRPV model uses the following three parameters describing the anisotropy of surface reflectance: (1) ρ_0, giving the diffuse reflectance; (2) k, representative of the bowl or bell shape of the surface anisotropy; (3) b, describing the predominance of forward or backward scattering. The RTnLS model is a semi-empirical kernel-driven model that consists of two kernel terms and a constant term. The volumetric kernel represents the scattering properties of a turbid medium, the geometric-optical kernel captures the shadowing effect of sparse vegetation, and the constant term is for the isotropic scattering. The weights for these three terms are called *vol*, *geo* and *iso*, respectively. RTnLS uses these weights to describe the anisotropy of surface reflectance. Support vector machine (SVM) and maximum likelihood classifiers (MLC) use the same inputs, and show the same tendency in terms of increases in accuracy. However, SVM can exploit the information carried by the same data sets more efficiently.

2. Study areas

Our study area lies within the Chihuahuan semi-desert province, which stretches across southeastern Arizona, southern New Mexico and western Texas. The intensive study sites are the Jornada Experimental Range in southern New Mexico near Las Cruces (approximately 78 266 ha centred at 32.5° N, 106.8° W) and the Sevilleta National Wildlife Refuge in central New Mexico near Albuquerque (approximately 100 000 ha, centred at 32.5° N, 106.8° W). The vegetation maps of the two sites were considered as ground reference data. These two vegetation type maps were produced using ground reconnaissance and aerial photos or TM images (Muldavin *et al.* 1998, Nolen *et al.* 1999). Vegetation types were envisioned as areas greater than 4 ha in the Jornada vegetation map. The Sevilleta vegetation map is with nominal 0.5 ha spatial resolution. The classifications adopted 19 classes from both extensive sites. Both sites are within the Chihuahuan desert and a number of the shrub and grass communities are similar (e.g. grama grass, creosotebush, tarbush), and communities are defined structurally as well as nominally, i.e. we are testing the hypothesis that information on canopy structure is carried by multiangle data and this should enable differentiation of classes based on canopy physiognomy. The MODIS and MISR data from 24 May to 3 June 2002, the end of the dry season, were selected in the study.

3. Method

MODIS/Terra is a cross-track scanner, which has viewing zenith angles on each side of nadir across track. The $\pm 55^\circ$ scanning pattern achieves a 2330 km swath and provides global coverage daily. MODIS uses the 'sequential' multi-angle concept to obtain directional information. In other words, MODIS obtains the multiple directional observations by accumulating them from daily single observations during a specific period of time. MISR, however, images the Earth almost simultaneously in nine different view directions along track. These cameras point at fixed angles, one viewing in the nadir direction (vertically downward, An camera) and four viewing in the forward (Af, Bf, Cf and Df camera) and afterward (Aa, Ba, Ca and Da camera) directions at 26.1, 45.6, 60.0 and 70.5 degrees respectively. The two MODIS data products used were: (1) the MODIS/Terra surface reflectance daily L2G global 250 m ISIN (Integerized Sinusoidal projection) grid (MOD09GQK) and (2) the MODIS/Terra geo-location angles daily L2G global 1 km SIN (Sinusoidal projection) grid day (MODMGGAD). The MODMGGAD product contains information on solar illumination and instrument viewing geometry angles. The MOD09GQK product provides surface spectral reflectance in red and near infrared bands with 250 m spatial resolution. The two MISR products used were: (1) the MISR level 1B2 MI1B2T terrain-projected product, providing top-of-atmosphere radiance with 275 m spatial resolution in nadir observation and red band, and 1.1 km spatial resolution in the off-nadir channels; (2) the MISR Level 1B2 MI1B2GEOP Geometric Parameters product, providing solar azimuth and zenith, sensors azimuth and zenith at 17.6 km spatial resolution. The MODIS and MISR data were resampled to the two experiment areas with 250 m spatial resolution. The simplified method for the atmospheric correction of satellite sensor measurements in the solar spectrum (SMAC) (Rahman and Dedieu 1994) was used to carry out atmospheric correction on the MISR radiance to estimate surface reflectance estimates.

To investigate the feasibility of combining the derived BRDF model parameters from MODIS observations and MISR reflectance to increase the accuracy of classification, a maximum likelihood classifier and support vector machine (Vapnik 1995) were employed to perform 36 experiments on 18 different inputs. In this study, the SVM computation used LIBSVM software (Chang and Lin 2006), and the radial basis functions were used as kernels. These 18 data sets consist of the various combinations of MISR-observed reflectance and the anisotropy patterns described by the MRPV and the RTnLS models (ρ_0, k, b and *iso*, *vol*, *geo*, respectively). These BRDF parameters were retrieved using three different datasets: MISR reflectance, MODIS reflectance and combined MISR and MODIS reflectance. Thus, three groups of BRDF parameters were obtained.

The experiment area covered by the Jornada and Sevilleta vegetation maps is 23 978 pixels (250 m spatial resolution) in total, approximately 1498 km^2. We randomly picked half (11 994 pixels) as a training set and another half (11 984 pixels) as a testing set for MLC and SVM classification.

Because the combination of MISR multi-spectral (blue, green, red and near infrared) nadir observations and off-nadir (Cf, Bf, Af, Aa, Ba, Ca camera) observations in the red and near infrared bands provides the highest accuracy (Su *et al.* 2005), this combination was considered the fundamental MISR multi-angular data set for the subsequent experiments. The short name of this dataset is 'MISR_multi-angle_plus', and the MISR nadir observations in four spectral bands are called 'MISR_nadir_plus' for these experiments.

4. Results and discussion

Tables 1 and 2 are the results of 36 classifications under MLC and SVM algorithms, respectively. The only difference between the two tables is the classification algorithm.

Table 1. Maximum likelihood classifications at combinations of observed reflectance and surface anisotropy patterns. (The units of accuracy and kappa index given in parentheses are percent*).

Data set		MISR	MODIS	MISR&MODIS
MISR nadir plus	$\rho_0 kb$	56.6(52.3)	50.0(45.8)	57.6(53.4)
	isovolgeo	62.0(58.0)	54.3(50.1)	56.8(52.7)
	$\rho_0 kb$_*isovolgeo*	65.0(61.0)	53.1(48.8)	61.1(57.0)
MISR multi-angle plus	$\rho_0 kb$	64.5(60.3)	64.6(60.4)	65.3(61.3)
	isovolgeo	65.5(61.5)	63.4(59.3)	64.6(60.5)
	$\rho_0 kb$_*isovolgeo*	67.5(63.6)	64.5(60.5)	67.2(63.3)

* MISR_nadir_plus has accuracy 45.8(41.1), MISR_multi-angle_plus has 60.9(56.5).

Tables 1 and 2 show the same tendency in terms of increased accuracy. However, SVM can exploit the information carried by the same data sets more efficiently. In general, the Jornada vegetation types were rarely confused with the Sevilleta ones. The grass, shrub and woodland community types of the Sevilleta usually were not confused. The misclassification between grass and shrub community types of the Jornada was also reduced considerably from the results based on nadir observations. The combination of the MISR_nadir_plus and the reflectance anisotropy patterns derived from the RTnLS model actually provides higher accuracy than the original MISR multi-spectral multi-angular observations. When the reflectance anisotropy patterns were obtained via inversion of the two BRDF models against MODIS reflectance ('MODIS' column), the classification accuracies are a little lower than the corresponding one from MISR reflectance ('MISR' column). When the patterns are obtained via inversion of the two BRDF models against combined MODIS and MISR reflectance ('MISR&MODIS' column), the classification accuracies also are a little lower than the corresponding one from MISR reflectance ('MISR' column). The only exception is the combination of the MISR_multi-angle_plus and the $\rho 0$, k, b of MRPV model against MODIS data or MODIS and MISR mixed data. This combination provides more accurate results than using MISR data alone. It is not surprising that the combined MODIS and MISR observations do not guarantee more helpful anisotropy patterns of surface reflectance for the classifications. The high calibration and geo-location accuracy of both MISR and MODIS instruments and the similarity of their spectral bands in the visible and near infrared enhance the ability to perform data fusion from these two sensors. Operationally, additional noise may still be introduced owing to the

Table 2. Support vector machine classifications at combinations of observed reflectance and surface anisotropy patterns. (The units of accuracy and kappa index given in parentheses are percent*).

Dataset		MISR	MODIS	MISR&MODIS
MISR nadir plus	$\rho_0 kb$	72.1(68.2)	70.4(66.3)	72.0(68.1)
	isovolgeo	74.6(71.1)	69.9(65.7)	72.5(68.6)
	$\rho_0 kb$_*isovolgeo*	75.6(72.2)	71.4(67.4)	73.9(70.2)
MISR multi-angle plus	$\rho_0 kb$	75.7(72.3)	76.2(73.0)	76.4(73.1)
	isovolgeo	76.6(73.4)	75.3(71.8)	75.8(72.5)
	$\rho_0 kb$_*isovolgeo*	76.7(73.5)	75.7(72.4)	76.5(73.2)

* MISR_nadir_plus has accuracy 64.3(59.1), MISR_multi-angle_plus has 75.6(72.2).

differences in spectral response functions, atmospheric correction schemes, and geometric registration of data from these two sensors. Moreover, MODIS uses the 'sequential' multi-angle concept to obtain directional information; while the MISR instrument uses the 'simultaneous' observation concept. MODIS is only able to collect comprehensive angular radiance via temporal compositing. MISR makes near-simultaneous, along-track multiple view angle measurements using nine cameras fixed in different forward and aft viewing directions. There is consequently a higher noise in the sequential observations than in the simultaneous observations.

The experiments also show that anisotropy patterns described by the MRPV and the RTnLS models are compatible with each other, because when they are used together, more accurate results will always be obtained. Moreover, the combinations of the MISR_nadir_plus set and the anisotropy patterns obtained by these BDRF models from MODIS observations basically produce the same accuracy as original MISR multi-angular observations. This reveals an innovative approach to increase classification accuracy and fusion of data from multiple satellites: a more accurate result can be expected when the classification uses both reflectance from nadir observing sensors and reflectance anisotropy patterns derived from 'sequential' or 'simultaneous' multi-angle observing sensors, such as MODIS, MISR, AVHRR and VEGETATION.

5. Conclusions

The current study demonstrates that anisotropy patterns of surface reflectance derived from MODIS observations are highly complementary to reflectance derived from MISR in differentiation of semi-arid vegetation types. This study also shows that:

(a) crucial additional information for classifications can be provided by the ρ_0, k, b parameter of the MRPV model and *iso*, *vol* and *geo* of the RTnLS model in the red and NIR bands;
(b) the SVM algorithm exploits the information carried by the same data sets more productively than MLC.

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