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# Variability in surface BRDF at different spatial scales (30 m–500 m) over a mixed agricultural landscape as retrieved from airborne and satellite spectral measurements

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ABSTRACT

Over the past decade, the role of multiangle remote sensing has been central to the development of algorithms for the retrieval of global land surface properties including models of the bidirectional reflectance distribution function (BRDF), albedo, land cover/dynamics, burned area extent, as well as other key surface biophysical quantities impacted by the anisotropic reflectance characteristics of vegetation. In this study, a new retrieval strategy for fine-to-moderate resolution multiangle observations was developed, based on the operational sequence used to retrieve the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5 reflectance and BRDF/albedo products. The algorithm makes use of a semiempirical kernel-driven bidirectional reflectance model to provide estimates of intrinsic albedo (i.e., directional-hemispherical reflectance and bihemispherical reflectance), model parameters describing the BRDF, and extensive quality assurance information. The new retrieval strategy was applied to NASA's Cloud Absorption Radiometer (CAR) data acquired during the 2007 Cloud and Land Surface Interaction Campaign (CLASIC) over the well-instrumented Atmospheric Radiation Measurement Program (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site in Oklahoma, USA. For the case analyzed, we obtained ~1.6 million individual surface bidirectional reflectance factor (BRF) retrievals, from nadir to 75° off-nadir, and at spatial resolutions ranging from 3 m to 500 m. This unique dataset was used to examine the interaction of the spatial and angular characteristics of a mixed agricultural landscape; and provided the basis for detailed assessments of: (1) the use of a land cover type-specific a priori knowledge in kernel-driven BRDF model inversions; (2) the interaction between surface reflectance anisotropy and instrument spatial resolution; and (3) the uncertainties that arise when sub-pixel differences in the BRDF are aggregated to a moderate resolution satellite pixel. Results offer empirical evidence concerning the influence of scale and spatial heterogeneity in kernel-driven BRDF models; providing potential new insights into the behavior and characteristics of different surface radiative properties related to land/use cover change and vegetation structure.

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## 1. Introduction

Techniques for determining the structure and optical properties of complex heterogeneous environments using multiangle remote sensing are crucial for understanding the effects of environmental change on vegetation structure and thus improve our ability to model terrestrial carbon cycle dynamics and to characterize the ecological functioning of many ecosystems. Recent studies have made considerable progress in developing algorithms for the extraction of quantitative information on terrestrial surface heterogeneity at the subpixel scale (Sandmeier et al., 1998; Widlowski et al., 2001; Pinty et al., 2002; Armston et al., 2007; Chopping et al., 2008; Hill et al., 2008). In general, this has been achieved by examining how different manifestations of the surface reflectance anisotropy over the angular range are directly related to canopy physiognomy and structure (e.g. canopy height, size, inter-distance between trees, and background vs. foliage contributions).

In the past, previous experiments have generally followed the central assumption that "the potential to detect structural heterogeneity is independent of the spatial scale corresponding to the pixel size" (Pinty et al., 2002). In line with this assumption, earlier studies have treated satellite BRDF/albedo retrievals as being observed over a homogeneous landscape; thus allowing direct "point-to-pixel" comparisons (Hautecoeur & Leroy, 1998; Liang et al., 2002; Jin et al., 2003a,b; Salomon et al., 2006; Chen et al., 2008; Knobelspiesse et al., 2008; Liu et al., 2009; Rutan et al., 2009). Recent studies have further evaluated surface albedo retrievals both in terms of the spatial

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correspondence (or representativeness) of the field (or tower-based) data and its relationship to the larger satellite pixel (Susaki et al., 2007; Román et al., 2009, 2010). However, because of the impact of view and solar zenith angle (SZA) dependencies, sub-grid scale spatial heterogeneity, and other underlying sources of variation that introduce measurement uncertainties within the ground resolution element (GRE) of satellite retrievals; the BRDF (and thus albedo) of certain ecosystems can only be correctly sampled with airborne multiangle measurements (Walthall et al., 2000). Among key biomes affected by these sources of error are mixed-forest canopies (Johnson, 1994; Russell et al., 1997), tropical savannas (Hill et al., 2008; Georgiev et al., 2009), shrublands (Chopping et al., 2004), as well as snow-covered environments (Lyapustin et al., 2010). Furthermore, recent studies contend that subpixel vegetation structure is only detectable when obtaining measurements near the principal plane; i.e., where BRDF effects are most pronounced (Chen et al., 2005). Consequently, the exact nature of these angular-to-structural relationships has been difficult to quantify at the relevant view-angle geometries of satellite sensors that routinely sample the BRDF over a single overpass (Leroy et al., 1997; Diner et al., 1998b) or in the course of multiple overpasses (Schaaf et al., 2002; Muller et al., 2007).

This study presents a new BRDF/albedo retrieval scheme that uses high quality, multiresolution, and multispectral surface bidirectional reflectance factor (BRF) measurements acquired by NASA's Cloud Absorption Radiometer (CAR) (King et al., 1986; Gatebe et al., 2003). The retrieval strategy, described in Section 2 and tested in Section 3 using data acquired over the well-instrumented Atmospheric Radiation Measurement Program (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART), is based on the operational Moderate Resolution Imaging Spectroradiometer (MODIS) algorithm for retrieving Surface Reflectance (Vermote et al., 1997; Kotchenova et al., 2006), BRDF and albedo (Schaaf et al., 2002, 2011).

Routine production of land surface BRDF retrievals is often achieved by compiling (or relying on) a global database of archetypal BRDF model reconstructions that seeks to describe the general anisotropic reflectance characteristics of terrestrial ecosystems, at several seasons whenever possible (Bicheron & Leroy, 2000; Strugnell et al., 2001; Lacaze et al., 2002; Bacour & Bréon, 2005). The BRDF associated with each location is then assumed to be governed by the character and structure of its land cover (Roujean et al., 1992; Román et al., 2009). In other cases, target-specific BRDF knowledge is used to supplement available observations and improve the quality of a retrieval. For instance, Jin et al. (2002) leveraged the BRDF model parameters derived from Multi-angle Imaging SpectroRadiometer (MISR) surface BRFs to bring additional information to the MODIS retrieval scheme; especially when the MISR observations were close to the principal plane. In either case (i.e., using target-specific or land cover type-specific knowledge), a priori information is being used to indicate when retrieved BRDF model parameters (or albedos) are outside the expected bounds. These approaches are based on Bayesian inference theory, which is considered to be the best way to make use of a priori knowledge to yield a posteriori estimates of unknown BRDF model parameters (Li et al., 2001).

In this study, the new BRDF/albedo retrieval scheme was used to examine the two major assumptions underlying the use of a land cover type-specific a priori knowledge in kernel-driven BRDF models (Lewis, 1995). The first assumption contends that “linear BRDF models can implicitly model surface heterogeneities”. The second one argues that “spatial degradation of modeled bidirectional reflectances can be achieved through degradation of the BRDF model parameters”. The assumptions were tested in parallel by comparing the relative model-fits (RMS) error from full-inversion retrievals (i.e., high-quality BRDF model inversions obtained directly from CAR measurements) against those that employ an ancillary database of archetypal BRDF model reconstructions to describe the surface anisotropy as either: (1) a linear-mixture of different land cover types; or (2) a single (or dominant) land cover type. In all cases, the RMS of relative error was obtained by simulating the surface BRF at the angular sampling of all observations over a given CAR grid cell; thus obtaining error estimates for various spectral bands and spatial scales (*cf.*, Section 4.1).

Because of the difficulties of estimating, validating, and conveying measurement differences between sensors and in-situ measurements, there is also a need to directly examine the accuracy, precision, and uncertainty (APU) of land surface BRDF products; particularly, across complex heterogeneous environments. Accordingly, the interaction between instrument spatial resolution and surface reflectance anisotropy was examined by assessing the distribution of relative differences in surface BRF retrievals obtained from CAR and MODIS BRDF model inversions at different spatial scales and across different spectral regions and view-angle geometries. Finally, the quality of MODIS Collection 5 (MCD43A1) surface BRF retrievals was evaluated across spatial scales to further quantify the uncertainties that arise when sub-pixel differences in the BRDF are aggregated to a moderate resolution satellite pixel (*cf.*, Section 4.2).

## 2. BRDF/albedo retrieval scheme

The new scheme has three main functional components: atmospheric correction (Fig. 1a), geolocation and gridding (Fig. 1b), and BRDF inversion (Fig. 1c). The aim of atmospheric correction is to retrieve surface-level bidirectional reflectance factor (BRF) measurements from remotely sensed CAR data, which is contaminated by the effects of atmospheric particles and gasses through absorption and scattering of the radiation, especially from the Earth's surface. The aim of geolocation and gridding is to determine the center coordinates of each observation along the instrument scan line (since the CAR data provide only the geolocation of the nadir-looking ground resolution element of each scan), and to register the data to a common grid to maintain consistency across datasets. The aim of BRDF inversion is to fit the RossThick-LiSparseReciprocal (RTLSR) BRDF model parameters to surface-level BRF measurements available over each CAR grid cell and spectral band. The retrieval scheme also performs angular integrations to derive intrinsic land surface albedos for each spectral band, and is supported by extensive quality assurance (QA) information.

### 2.1. Atmospheric correction

In the past, various radiative transfer (RT) schemes have been used for the atmospheric correction of CAR data (*cf.*, Gatebe et al., 2003, 2005; Lyapustin et al., 2010). In this study, we used the second simulation of satellite signal in the solar spectrum (6S) model, version 6SV1.1 (Vermote et al., 1997; Kotchenova et al., 2006), which is the heritage model used in the operational MODIS algorithm for retrieving Surface Reflectance. The 6S code is an RT model based on the successive orders of scattering method. The spectral resolution of the model is 2.5 nm, and the aerosol layer is divided into 13 layers with a scale height of 2 km. The model assumes the atmosphere consists of radioactively active fixed gasses: $O_2$, $O_3$, $H_2O$, $CO_2$, $CH_4$, and $N_2O$. The concentration of $O_2$, $CO_2$, $CH_4$, and $N_2O$ is assumed to be constant and uniformly mixed in the atmosphere. The 6S model allows us to determine the attenuation of solar irradiance under cloudless conditions at the surface. It removes the effects of Rayleigh scattering, aerosol attenuation, and ozone and water vapor absorption, provided we know the key characteristics of the atmosphere, such as the atmospheric optical thickness, aerosol model, and absorbing gas concentration. Since the CAR measurements were acquired during intensive field campaigns, coincident and co-located ground-based and airborne data needed as input to the 6S model exist. For example, aerosol parameters can be obtained from ground-based sunphotometer measurements (Holben et al., 1998), or from the Ames Airborne Tracking Sunphotometer (Russell et al., 1999), or retrieved from CAR measurements (Fig. 1a) (Gatebe et al., 2010).