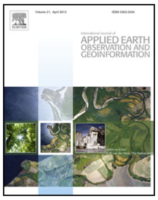
International Journal of Applied Earth Observation and Geoinformation 43 (2015) 102–118

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



# Observing system simulations for small satellite formations estimating bidirectional reflectance

Sreeja Nag[a,b,*], Charles K. Gatebe[b,c], Olivier de Weck[a]

[a] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[b] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[c] *Universities Space Research Association, Columbia, MD 21046, USA*

ARTICLE INFO

*Article history:*
Received 1 November 2014
Accepted 30 April 2015
Available online 4 September 2015

*Keywords:*
Multi-angular remote sensing
Small satellite
Formation
BRDF
OSSE

ABSTRACT

The bidirectional reflectance distribution function (BRDF) gives the reflectance of a target as a function of illumination geometry and viewing geometry, hence carries information about the anisotropy of the surface. BRDF is needed in remote sensing for the correction of view and illumination angle effects (for example in image standardization and mosaicing), for deriving albedo, for land cover classification, for cloud detection, for atmospheric correction, and other applications. However, current spaceborne instruments provide sparse angular sampling of BRDF and airborne instruments are limited in the spatial and temporal coverage. To fill the gaps in angular coverage within spatial, spectral and temporal requirements, we propose a new measurement technique: Use of small satellites in formation flight, each satellite with a VNIR (visible and near infrared) imaging spectrometer, to make multi-spectral, near-simultaneous measurements of every ground spot in the swath at multiple angles. This paper describes an observing system simulation experiment (OSSE) to evaluate the proposed concept and select the optimal formation architecture that minimizes BRDF uncertainties. The variables of the OSSE are identified; number of satellites, measurement spread in the view zenith and relative azimuth with respect to solar plane, solar zenith angle, BRDF models and wavelength of reflection. Analyzing the sensitivity of BRDF estimation errors to the variables allow simplification of the OSSE, to enable its use to rapidly evaluate formation architectures. A 6-satellite formation is shown to produce lower BRDF estimation errors, purely in terms of angular sampling as evaluated by the OSSE, than a single spacecraft with 9 forward-aft sensors. We demonstrate the ability to use OSSEs to design small satellite formations as complements to flagship mission data. The formations can fill angular sampling gaps and enable better BRDF products than currently possible.

## 1. Introduction

Multi-angular remote sensing, or sensing of the same target at multiple angles, is very important for obtaining various science products such as albedo, for land cover classification, for cloud detection, for atmospheric correction (Gatebe, 2003). Sparse angular sampling of the reflected light can cause errors between 15% and 90% in the reflectance products of moderate resolution, solar wavelength remote sensing (Esper et al., 2000; Nag, 2015). Up to 90% of the errors in the computation of radiative forcing, a key assessor of climate change, is attributed to the lack of detailed description of reflected solar flux (Wielicki and Harrison, 1995). Total Outgoing Radiation (TOR) is estimated at 0.9 W/m$^2$ by current climate models—with uncertainties of −2 to +7 W/m$^2$ (Loeb et al., 2009), reduced only by frequent, global, angular radiance measurements (Dyrud et al., 2014). Snow albedo when estimated using only nadir reflectance shows up to 45–50% errors compared to hemispherical reflectance (Arnold et al., 2002). Current Gross Primary Productivity (GPP) estimates show uncertainties up to 40% in the terrestrial carbon uptake (Hilker et al., 2011). Vegetation analysis is adversely affected by under-sampling on the principal plane and hotspots (Román et al., 2011). GPP and vegetation reflectance quantifies the extent to which forests and vegetation act as a sink for atmospheric carbon dioxide and is very important to estimate carbon feedbacks of vegetation in response to global climate change (Canadell et al., 2007). Deforestation and forest degradation accounts for 12% of anthropogenic carbon emissions, which have nearly doubled in the past 30 years (Van der

---

[*] Corresponding author at: Bay Area Environmental Research Institute, Sonoma, CA 95476, USA.
*E-mail address:* sreejanag@alum.mit.edu (S. Nag).

http://dx.doi.org/10.1016/j.jag.2015.04.022
0303-2434/

Werf et al., 2009). Recent studies have also shown an overestimation of the greening of Amazon forests during the dry season due to seasonal artifacts in MODIS' sun-sensor geometry (Morton et al., 2014). Using denser, space-based angular sampling from the CHRIS instrument (Barducci et al., 2005) reduces GPP uncertainties to 10% (Hall et al., 2008), showing a 75% improvement in carbon cycle calculations. The above shortcomings will not disappear but can be significantly improved by better angular sampling of the BRDF function.

This paper proposes a new measurement solution for multi-angular remote sensing and details the observing system simulation experiment (OSSE) designed to optimize the solution, with the goal of selecting a few optimal mission designs. The measurement solution is intended to complement current flagship and Decadal Survey missions, by alleviating some sampling requirements that could cause creeps. The Earth Science Decadal Surveyasked for "*Synergies of complementary measurements...cost-effective replacement of individual sensors... moving away from a single parameter and sensor-centric approach toward a systems approach that ties observations together to study processes important to understanding Earth-system feedbacks*" when proposing 15 instruments for the next decade (National Academy of Sciences, 2007). Seven years later, only 3 of those are in formulation, causing the Survey's mid-term assessment to stress on complementary solutions like hosted payloads and formation flight (National Research Council, 2012). The proposed solution in this paper seeks to do the same, by identifying a quantifiable gap in Earth remote sensing and addressing it using small satellite formations.

The presented OSSE is a subset of a larger evaluation framework, which generates and evaluates the engineering design tradespace of solutions. The models within the OSSE have been carefully evaluated in the context of space-based measurements by formations and the surface types expected to be sampled over time. Reference data are designated from a combination of airborne and spaceborne data collected over NASA campaigns and missions, respectively, and validated using radiative transfer models. The design, nature and validation of the OSSE are indispensable to the selection of the optimal measurement solution owing to the complexity of distributed missions. A baseline design has been proposed in the case study, and its multi-angular advantages to other candidate designs and over a monolithic counterpart demonstrated using the developed OSSE.

### 1.1. *Why Bi-directional reflectance?*

The bidirectional reflectance distribution function (BRDF) gives the reflectance of a target as a function of illumination geometry and viewing geometry, hence carries information about the anisotropy of the surface (Gatebe, 2003). BRDF itself, as a ratio of infinitesimals, is a derivative with instantaneous values of reflected radiance and solar illumination (Nicodemus, 1977). BRDF is influenced by intrinsic properties of the reflecting surface that can be measured within the surface itself without any reference to a larger space. While it can never be measured directly, real measurements can involve non-zero intervals of above parameters. It depends on four major angles—the solar zenith angle or SZA, solar azimuth angle, view zenith angle or VZA and view azimuth angle—as well as onthe wavelength of light (Gatebe, 2003). The azimuth angles are added to provide one azimuth angle relative to the solar position called the relative azimuth angle or RAA. Estimating BRDF (Barnsley et al., 1994) requires radiance measurements across a large angular spread, with spectral range over the visible and near infrared (VNIR) solar spectrum and with spatial resolution that is appropriate of sampling BRDF ofsurface types of interest. Frequent temporal measurements can allow monitoring of regions of interest, and allow global coverage orglobal. To name a few applications, BRDF is used for the derivation of surface albedo (Lyapustin et al., 2010), calculation of radiative forcing (Liang, 2008), land cover classification (Privette et al., 1997), gross primary productivity (Hilker et al., 2008), cloud detection (Esper et al., 2000), surface roughness measurements of vegetation, snow or ice (Gatebe, 2003; Chopping, 2008), canopy structure (Chopping, 2008; Chopping et al., 2008), atmospheric corrections, and aerosol optical properties (Gatebe, 2003).

### 1.2. *Gaps in current measurements*

Current measurement techniques are inadequate for estimating global BRDF. Spacecraft instruments approximate BRDF by making multi-angular measurements owing to their large cross-track swath (e.g. Moderate Resolution Imaging Spectroradiometer-MODIS (Xiong et al., 2011), now retired Polarization and Directionality of the Earth's Reflectances-POLDER (Deschamps et al., 1994), Clouds and Earth's Radiant Energy System-CERES (Wielicki et al., 1996), multiple forward and aft sensors (e.g. Multi-angle Imaging SpectroRadiometer-MISR (Diner et al., 1998), Along Track Scanning Radiometer-ATSR (Godsalve, 1995), Advanced Spaceborne Thermal Emission and Reflection Radiometer-ASTER (Abrams, 2000), or autonomous maneuverability to point at pre-programmed ground targets (e.g. Compact High Resolution Imaging Spectrometer -CHRIS (Barducci et al., 2005).

Since angular sampling requires simultaneous reflectance measurements at multiple angles for a given ground footprint, one satellite is insufficient for accurate characterization. A single large, complex satellite (monolith), especially a forward-aft or cross-track sensors in sun synchronous orbits (SSO) such as MISR or MODIS, can make measurements only along a restrictive plane with respect to the solar phase because SSOs have nearly constant beta angles and local crossing times. Angular reflectance acquisition by monoliths typically combines measurements along-track if they have forward-aft sensors (Fig. 1-left) or cross-crack if they have a large swath (Fig. 1-right). Measurements made by cross-track sensors are separated in time by more than a week (e.g. MODIS, CERES). In areas of fast changing surface/cloud conditions especially during the melt season/tropical storms, a few days can make a big difference in reflectance. The three shown look angles in Fig. 1 are only examples. In reality, many such measurements are combined.

Spaceborne instruments that provide good angular sampling compromise in other sampling characteristics. Table 1 compares seven spaceborne instruments with BRDF-dependent products in terms of angular sampling (Col #1), spatial resolution (Col #2), temporal resolution (Col #3) and spectral range and resolution (Col #4 and #5). The number of angles indicate near simultaneous angular measurements of the same ground spot and RGT is the repeat ground track period. Since our proposed measurement solution is expected to make near-simultaneous angular measurements, the time of acquisition in Table 1 is restricted to a few minutes to make a fair comparison. POLDER, MISR and CHRIS provide many angular measurements, but POLDER has very coarse ground resolution, CHRIS has no target repeatability for temporal monitoring of surface types and MISR is restricted to only four bands in VNIR and to near-constant solar phase. MODIS and CERES are cross-track sensors so they get only one view at one angle every orbit, of the same ground spot. ATSR and ASTER, with their double cameras, are able to scale this up to two angles every orbit. However, their long repeat period and narrow swath, respectively, limit how quickly they can accumulate good sampling.

Airborne instruments can provide dense angular, spectral sampling at fine spatial resolution but it is very expensive to make frequent, repeated measurements globally. NASA GSFC's heritage airborne BRDF instrument, the Cloud Absorption Radiometer (CAR) (King et al., 1986), has 14 channels and can make up to 114.600