Acta Astronautica 126 (2016) 77–97

Contents lists available at ScienceDirect

Acta Astronautica

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

Effect of satellite formations and imaging modes on global albedo estimation

Sreeja Nag [a,*], Charles K. Gatebe [b], David W. Miller [c], Olivier L. de Weck [d]

[a] NASA Goddard Space Flight Center, MD/Bay Area Environmental Research Institute, CA, USA
[b] NASA Goddard Space Flight Center/Universities Space Research Organization, MD, USA
[c] NASA Headquarters/Massachusetts Institute of Technology, MA, USA
[d] Massachusetts Institute of Technology, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 7 January 2015
Received in revised form
27 February 2016
Accepted 4 April 2016
Available online 6 April 2016

Keywords:
Small satellite
Formation flight
Cubesat
BRDF
Multi-angular
Remote sensing
Constellation

ABSTRACT

We confirm the applicability of using small satellite formation flight for multi-angular earth observation to retrieve global, narrow band, narrow field-of-view albedo. The value of formation flight is assessed using a coupled systems engineering and science evaluation model, driven by Model Based Systems Engineering and Observing System Simulation Experiments. Albedo errors are calculated against bi-directional reflectance data obtained from NASA airborne campaigns made by the Cloud Absorption Radiometer for the seven major surface types, binned using MODIS' land cover map – water, forest, cropland, grassland, snow, desert and cities. A full tradespace of architectures with three to eight satellites, maintainable orbits and imaging modes (collective payload pointing strategies) are assessed. For an arbitrary 4-sat formation, changing the reference, nadir-pointing satellite dynamically reduces the average albedo error to 0.003, from 0.006 found in the static reference case. Tracking pre-selected waypoints with all the satellites reduces the average error further to 0.001, allows better polar imaging and continued operations even with a broken formation. An albedo error of 0.001 translates to 1.36 W/m^2 or 0.4% in Earth's outgoing radiation error. Estimation errors are found to be independent of the satellites' altitude and inclination, if the nadir-looking is changed dynamically. The formation satellites are restricted to differ in only right ascension of planes and mean anomalies within slotted bounds. Three satellites in some specific formations show average albedo errors of less than 2% with respect to airborne, ground data and seven satellites in any slotted formation outperform the monolithic error of 3.6%. In fact, the maximum possible albedo error, purely based on angular sampling, of 12% for monoliths is outperformed by a five-satellite formation in any slotted arrangement and an eight satellite formation can bring that error down four fold to 3%. More than 70% ground spot overlap between the satellites is possible with 0.5° of pointing accuracy, 2 Km of GPS accuracy and commands uplinked once a day. The formations can be maintained at less than 1 m/s of monthly ΔV per satellite.

1. Introduction

Distributed Space Missions (DSMs) are gaining momentum in their application to earth science missions owing to their ability to increase observation sampling in spatial, spectral, temporal and angular dimensions. DSMs include homogenous (such as RapidEye [1]) and heterogeneous constellations (such as Cosmo-SkyMed [2], QB50 [3], Disaster Monitoring Constellation/DMC [4], NASA A-Train), autonomous formation flying formations (such as Tandem-X [5], Proba-3 [6], PRISMA [7]) and fractionated spacecraft (such as DARPA System F6 [8], JPL's Phoenix cellularized architecture [9]). To avoid being cost prohibitive, small satellites will be required to enable DSMs, especially those with large numbers. Small satellites (< 50 kg) have technically demonstrated formation technologies [10] and missions such as CanX-4 and CanX-5 [11] are now (2015) beginning to show formation flight feasibility using CubeSats.

In Earth science remote sensing, distributed space missions or DSMs have been traditionally used to simultaneously

* Corresponding author.
E-mail addresses: sreejanag@alum.mit.edu (S. Nag), Charles.K.Gatebe@nasa.gov (C.K. Gatebe), millerd@mit.edu (D.W. Miller), deweck@mit.edu (O.L. de Weck).

http://dx.doi.org/10.1016/j.actaastro.2016.04.004
0094-5765/

improve sampling in the following four dimensions of an observed image – spatial, temporal, spectral, and radiometric. Spatial resolution of an image can be increased by using multiple satellites in formation flight to synthesize a long baseline aperture as shown for optical interferometry [12–14] and synthetic aperture radars [5,15–17]. Constellations of evenly spaced satellites on repeat track orbits [2,4] ensure temporal sampling within a few hours as well as continuous coverage maintenance. Spectral sampling can be improved by fractionating the payload (fractionated spacecraft) such that each physical entity images a different part of the spectrum and has customized optics to do so. Radiometric resolution depends on the resolution of the other sampling dimensions for a fixed instrument mass and complexity. Since DSMs allow sampling improvement in any dimension by increasing satellite number instead of size, radiometric resolution can be improved without compromising on other science sampling requirements.

Formations have enabled science that cannot be performed with single spacecraft, such as gravimetry by GRACE [18] and GRAIL [19] or coronographs using nulling occultors like DARWIN [13]. This paper and associated research focuses on improving angular sampling, which is a critical dimension for Earth observations. Angular sampling implies taking images of the same ground spot at multiple 3D angles of solar incidence and reflection simultaneously. Lack of such sampling leads to misinterpretation in science products, for example, Amazon greenness from MODIS data [20]. The requirement to make near-simultaneous measurements deems monoliths less optimal for accurate and dense angular sampling than distributed systems [21,22]. Monolithic spacecraft have traditionally approximated the angular samples by combining measurements taken over time with forward-aft (e.g. TERRA's MISR [23]) or cross-track swath (e.g. TERRA's MODIS [24]) sensors or autonomous manoeuvrability (e.g. CHRIS [25] on Proba-3). However, a single satellite can make measurements only along a restrictive plane with respect to the solar phase and most Earth observation satellites are even more restricted since they are on sun-synchronous orbits. Further, the angular measurements are separated in time by many minutes along-track or more than a week cross-track. In areas of fast changing surface/cloud conditions especially during the snow melt season/tropical storms, a few days can make a big difference in reflectance. Those that autonomously manoeuvre have to be commanded to observe specific targets, thus lack global coverage and repeatability.

Near-simultaneous angular sampling can be improved by using a formation or constellation of nanosatellites [26]. The formation can make multi-spectral measurements of a ground spot at multiple 3D angles at the same time as they pass overhead by using narrow field of view instruments in controlled formation flight. While this measurement-making mechanism was suggested more than ten years ago (Leonardo BRDF [21,27]), it never went past the concept ideation stage and no detailed analysis was performed on its science impact or technical feasibility. Recent literature [22,28] has shown that closed loop and maintainable formations and spectrometer payloads are available for multi-angular formation flight. The widely accepted metric to quantify the angular dependence of remotely sensed signal is BRDF or Bidirectional

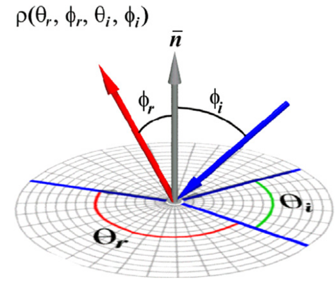

Fig. 1. BRDF geometry and angles in terms of two vectors – incoming solar irradiance (blue) and outgoing reflected radiance (red), measured at VNIR wavelengths (figure adapted from University of California Berkeley's open-source, open-access class curriculum at http://www.eecs.berkeley.edu/). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Reflectance-distribution function. BRDF of an optically thick body is a property of the surface material and its roughness. It is the ratio of reflected radiance to incident irradiance that depends on 3D geometry of incident and reflected elementary beams [29]. It depends on four major angles as shown in Fig. 1 – the solar zenith angle (ϕ_i), solar azimuth angle (θ_i), measurement zenith angle or the co-elevation (ϕ_r) and measurement azimuth angle (θ_r). The azimuth angles, θ_i and θ_r, are added to provide one angle called the relative azimuth angle. Several review studies have confirmed the applicability of BRDF accuracy as a reliable metric to design new measurement solutions in multi-angular remote sensing [31]. BRDF is required for the calculation of many Earth Science products such as albedo, vegetation indices, photosynthetic activity and ice cloud optical properties [30], therefore BRDF estimation accuracy affects estimation accuracy of all its dependents. This paper will demonstrate the simulated impact of different variables in formation design on the accuracy of albedo, calculated from retrieved BRDF, globally.

Albedo is the hemispherical integration of BRDF over all measurement zenith and azimuth angles, for a single solar incidence direction (black sky albedo) or all solar incidence (white sky albedo). Inaccurate estimation of BRDF significantly affects narrow-band, narrow-field-of-view albedo estimation. The NASA ARMCAS airborne campaign [32] of 1998 in Alaska measured reflectance at thousands of zenith and azimuth angles using the Cloud Absorption Radiometer (CAR) that was flown around in circles on an airplane and estimated albedo using these measurements. Nadir reflectance albedo, when compared to albedo estimated from integrating hemispherical measurements, shows up to 50% error. The error depends on the wavelength or location (sea ice vs. tundra) sampled. A more recent study [33] shows 15%–20% difference between vegetation albedo estimated using CAR compared to MODIS albedo products.

The Earth's albedo has been an important component of climate studies and the Earth Radiation Budget since the 1960s [34]. Incoming radiation is measured better than 0.03% of 1368 W/m^2 but total outgoing radiation is accurate to just 1% of 341.3 W/m^2, causing an imbalance called the 'missing energy [35,36]. Narrow-band albedo uncertainties of surfaces such as polar ice caps are one of the three biggest contributors [37] to our lack of understanding of the Earth Radiation Imbalance. Improving albedo estimation by even 0.0025 corresponds to