Remote Sensing of Environment 170 (2015) 62–76

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Virtual constellations for global terrestrial monitoring

Michael A. Wulder [a,*], Thomas Hilker [b], Joanne C. White [a], Nicholas C. Coops [c], Jeffrey G. Masek [d], Dirk Pflugmacher [e], Yves Crevier [f]

[a] Canadian Forest Service, Pacific Forestry Center, Natural Resources Canada, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada
[b] College of Forestry, Oregon State University, Corvallis, OR 97331, USA
[c] Department of Forest Resource Management, Forest Sciences Centre, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada
[d] Biospheric Sciences Branch, Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD 20771, USA
[e] Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
[f] Earth Observation Applications and Utilization, Space Utilization Directorate, Agence Spatiale Canadienne|Canadian Space Agency, 6767, route de l'Aéroport, Saint-Hubert, QC J3Y 8Y9, Canada

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 31 August 2015
Accepted 14 September 2015
Available online 22 September 2015

Keywords:
Satellite
Constellation
Monitoring
Land cover
Land use
Science
Landsat
Sentinel-2

ABSTRACT

Free and open access to satellite imagery and value-added data products have revolutionized the role of remote sensing in Earth system science. Nonetheless, rapid changes in the global environment pose challenges to the science community that are increasingly difficult to address using data from single satellite sensors or platforms due to the underlying limitations of data availability and tradeoffs that govern the design and implementation of currently existing sensors. Virtual constellations of planned and existing satellite sensors may help to overcome this limitation by combining existing observations to mitigate limitations of any one particular sensor. While multi-sensor applications are not new, the integration and harmonization of multi-sensor data is still challenging, requiring tremendous efforts of science and operational user communities.

Defined by the Committee on Earth Observation Satellites (CEOS) as a “set of space and ground segment capabilities that operate in a coordinated manner to meet a combined and common set of Earth Observation requirements”, virtual constellations can principally be used to combine sensors with similar spatial, spectral, temporal, and radiometric characteristics. We extend this definition to also include sensors that are principally incompatible, because they are fundamentally different (for instance active versus passive remote sensing systems), but their combination is necessary and beneficial to achieve a specific monitoring goal. In this case, constellations are more likely to build upon the complementarity of resultant information products from these incompatible sensors rather than the raw physical measurements. In this communication, we explore the potential and possible limitations to be overcome regarding virtual constellations for terrestrial science applications, discuss potentials and limitations of various candidate sensors, and provide context on integration of sensors. Thematically, we focus on land-cover and land-use change (LCLUC), with emphasis given to medium spatial resolution (*i.e.*, pixels sided 10 to 100 m) sensors, specifically as a complement to those onboard the Landsat series of satellites. We conclude that virtual constellations have the potential to notably improve observation capacity and thereby Earth science and monitoring programs in general. Various national and international parties have made notable and valuable progress related to virtual constellations. There is, however, inertia inherent to Earth observation programs, largely related to their complexity, as well as national interests, observation aims, and high system costs. Herein we define and describe virtual constellations, offer the science and applications information needs to offer context, provide the scientific support for a range of virtual constellation levels based upon applications readiness, capped by a discussion of issues and opportunities toward facilitating implementation of virtual constellations (in their various forms).

1. Introduction

Remotely sensed observations acquired from Earth orbiting spacecraft are fundamental to understanding Earth system functioning and the effects of natural and human-induced changes on the global environment (Cohen & Goward, 2004). Since the launch of the first Landsat sensor in 1972, active and passive remote sensing has provided critical input to Earth system models, ranging from atmospheric composition to the status of the terrestrial biosphere (Belward & Skøien, 2015). The scientific and technological progress in Earth observation over the last 40 years is unparalleled; however, the challenges faced by the Earth science community are immense: global climate has now entered a period of rapid change as humans are altering the composition of the atmosphere (McMullen & Jabbour, 2009; Woods, Heppner, Kope, Burleigh, & Maclauchlan, 2010), and scientists are faced with the task of assessing

---

* Corresponding author.
E-mail address: mike.wulder@canada.ca (M.A. Wulder).

http://dx.doi.org/10.1016/j.rse.2015.09.001

the risks associated with these changes, their feedbacks on the global carbon and energy cycle, and the consequences for life on Earth (Bentz et al., 2010; Kurz et al., 2008; Price et al., 2013).

The most recent report of the IPCC (2014) outlines the links between anthropogenic activity and observed changes in the climate system. These human activities include changes to global land cover and land use, with associated ramifications that range from the capacity of Earth systems to sequester CO_2 from the atmosphere and absorb solar energy (Pielke et al., 2002), through to the alteration of the natural disturbance regimes of forested ecosystems (Dale et al., 2001). The way in which land is used results in difficult trade-offs between meeting present day human needs (food, shelter, economic opportunity) while also maintaining the future capacity of the biosphere to continue meeting those same needs (Foley et al., 2005). Land use conversions are often made to accommodate human needs for agricultural production, living or commercial space, as well as industrial or transportation infrastructure. Depending on the type of conversion, permanent changes in land cover can have a range of impacts, such as a loss of carbon stocks as a result of biomass burning or conversion of forests to agricultural lands (Fearnside, 2000; Pielke et al., 2002) as well as changes to the provision of a broad range of ecosystem services (Naidoo et al., 2008).

The rapid nature and the scale of land-cover and land-use change (LCLUC) poses challenges to the remote sensing community, as a full understanding of anthropogenic impacts and their feedbacks on ecosystems will require frequent (Scheller et al., 2007) and comprehensive observations across large areas (Hansen et al., 2008; Laurance et al., 2012; Townshend et al., 2012). From regional and global monitoring perspectives, despite the progress made over the last several decades, contemporary scientific advancement remains limited by the data available to researchers and the trade-offs between spatial, temporal, spectral, and radiometric sensor characteristics that govern remote sensing instrument design (Wulder et al., 2008). For instance, high spatial resolution imagery typically results in a smaller image footprint, or spatial extent, thereby increasing the time it takes for a satellite to revisit the same location on Earth (Hilker, Wulder, Coops, Linke, et al., 2009; Hilker, Wulder, Coops, Seitz, et al., 2009). It is worth noting that reported temporal revisit of high spatial resolution sensors includes the use of pointable observatories. As an example, the revisit time for a given location can be about 4 days using off-nadir viewing (both cross-track and in-track), or 144 days if true nadir viewing is required (Wulder, Ortlepp, White, & Coops, 2008). While some deviation off nadir may be required to create more data collection opportunities, tolerance for off-nadir viewing is determined by the needs of a given application and by consideration of factors such as the level of geometric and illumination consistency required for automated applications over time, both for objects of interest (*i.e.*, trees), and between adjacent images (Wulder, White, et al., 2008; Wulder, Ortlepp, White and Coops, 2008). High temporal resolution sensors such as NOAA's Advanced Very High Resolution Imaging Spectroradiometer (AVHRR) and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) have a more frequent revisit rate (daily) coupled with a wider imaging swath, resulting in wide-area coverage at a lower spatial resolution (Holben, 1986; Roy et al., 2008). Outside of government realms, there are successful examples of commercial satellite constellations, including DMC and BlackBridge RapidEye (Powell, Pflugmacher, Kirschbaum, Kim, & Cohen, 2007). Constellations (or swarms) of microsats (including cubesats) are also emerging (Hand, 2015; Butler, 2014). Generally of notably lower cost and operating at lower orbits with a small total satellite size and weight, these microsats have radiometric and geometric considerations that remain to be addressed (Butler, 2014). The presence of this wide range of sensors offers users with options for sourcing data, as well as many considerations to ensure compatibility and rigor in subsequent analyses.

One approach to help meet application and information needs while also mitigating the aforementioned challenges, as summarized above, is to combine sensors with similar characteristics into so-called *virtual constellations*. Satellite constellations have long been used to add value to Earth observations by combining sensors with complementary characteristics. For example, NASA's "afternoon constellation" (so-called "A-train") consists of satellites passing in the same sun-synchronous polar orbit within minutes of each other (http://www.nasa.gov/mission_pages/a-train/a-train.html). This formation flying allows near-simultaneous observations of a variety of parameters to aid the scientific community in understanding Earth–atmosphere interactions and advancing Earth system science. The value of the near simultaneous measures associated with the A-train has been recognized, and the potential inclusion of any new satellite in the A-train is now undertaken with specifically designed scientific objectives in mind (*e.g.* Stephens et al., 2002). Virtual constellations are similar in concept, but have come from more organic beginnings. Virtual constellations capitalize on existing capacities of current sensors and their orbits with the aim to identify and understand possible synergies of satellite observations from sensors with similar spatial, spectral, temporal, and radiometric characteristics in order to expand the scope of space-based Earth system science by producing a consistent and calibrated set of Earth observations to meet the needs of a particular domain area. The Committee on Earth Observation Satellites (CEOS) defines virtual constellations as a "set of space and ground segment capabilities that operate in a coordinated manner to meet a combined and common set of Earth Observation requirements." Herein, we broaden this definition to include virtual constellations in which the sensors themselves may have disparate characteristics and observations, but they offer complementary information that is of synergistic value. In this paper, we review the potential of virtual constellations for LCLUC and describe the concept, motivation, characteristics, and forward-going opportunities for the development of virtual constellations targeted at monitoring LCLUC. In so doing, we characterize three different types of virtual constellations according to their application-readiness. We discuss the potential of virtual constellations for improving and complementing medium spatial resolution (pixel resolution of 10–100 m) data sets, addressing spatial versus temporal trade-offs, as well as overall benefits for land surface observations. Our overarching objective is to elucidate the potentials of virtual constellations for LCLUC and identify key research priorities that could support implementation and expand opportunities for virtual constellations to contribute toward enhanced global monitoring capacity.

2. Land-cover and land-use change mapping context for virtual constellations

LCLUC is the complex result of a combination of resource scarcity, market opportunities, policy intervention, and changes in social organization and attitudes (Rindfuss, Walsh, Turner, Fox, & Mishra, 2004; Lambin, Geist, & Lepers, 2003). In recent years, the study of LCLUC has moved from simplistic representations of change to recognition of a complex co-evolution of natural and social systems across different spatial and temporal scales (Lambin et al., 2003; Lepers et al., 2005). While significant progress has been made in reducing LCLUC uncertainties, much remains to be learned about interactions between changes in vegetation properties on one side, and carbon sequestration, provision of ecosystem services, maintenance of biodiversity, and ecosystem degradation on the other (McKinley et al., 2011; Rittenhouse & Rissman, 2012). For instance, initial research has focused on *land-cover conversions* (*i.e.*, the complete replacement of one cover type by another) as a major contributor to land carbon emissions, but in recent years the importance of more subtle *land-cover modifications* and ecosystem degradation has increasingly been recognized (Lambin et al., 2003; Houet et al., 2009). Both land-cover conversions and modifications can be difficult to detect in the presence of phenological and climate related interannual changes in vegetation (Singh, 1989), yet their impact on ecosystems and carbon cycling is considerable (Foley et al., 2005). A comprehensive understanding of LCLUC therefore requires observations and