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Radiometric cross-calibration of Gaofen-1 WFV cameras using Landsat-8 OLI images: A solution for large view angle associated problems

Lian Feng [a], Juan Li [b], Weishu Gong [c], Xi Zhao [b], Xiaoling Chen [a], Xiaoping Pang [b,*]

[a] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China
[b] Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan 430079, China
[c] Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA

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ABSTRACT

Four wide-field-of-view (WFV) instruments are onboard the Gaofen-1 (or GF-1) satellite, providing a combined swath of ~800 km. However, observations with large view angles pose new challenges for radiometric cross-calibration with a simple image-based method when using Landsat-8 Operational Land Imager (OLI) data as a reference. Based on radiative transfer modeling, a novel radiometric cross-calibration method has been proposed in this study to solve large view angle-associated problems. The Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol products were used to simulate the top of atmosphere (TOA) signal of the reference and target instruments, and the unequal bidirectional effects were corrected using MODIS bi-directional reflectance distribution function (BRDF) products. Extensive validations with both satellite data and in situ measurements revealed an uncertainty of ~8% for the newly produced cross-calibration coefficients when they were used to calibrate TOA reflectance for both close-nadir and off-nadir instruments. The improvements are discernable when compared with the official provided coefficients and that were derived using the image-based cross-calibration method. This study demonstrated not only the usefulness of Landsat-8 OLI data in sensor radiometric calibration but also the impressive accuracy of the MODIS BRDF and aerosol products in radiative transfer simulations. The proposed method can be used in the future to monitor and correct potential radiometric degradations of the GF-1 WFV instruments, and it also can be easily extended to other similar satellite missions to conduct radiometric cross-calibrations.

1. Introduction

Because of the promotion of the high-definition earth observation system (HDEOS) by the Chinese government, two high-resolution satellite missions, Gaofen-1 (or GF-1, 2013–present) and Gaofen-2 (or GF-2, 2014–present), have been successfully launched into space. Another three or four satellites in HDEOS are expected to be launched in the next ten years (Xu, Gong, & Wang, 2014). Currently, the images acquired by GF-1 are available to the public after authorization. Four high spatial resolution (16 m) wide-field-of-view (WFV) cameras are onboard the GF-1 satellites, providing a revisiting period of 4 days due to their wide combined coverage (4 × 200 km). In the past two years, the GF-1 images have been used in numerous applications, including searching for evidence in criminal cases and monitoring disasters, among many others, as reported by various mass media.

The potential uses for the GF-1 WFV images are not limited to these qualitative applications. The high spatial-temporal resolution and wide coverage make it possible to capture and understand biological, chemical, and physical processes on both small and large scales. Accurate radiometric calibration, however, is required before the satellite signal can be linked to any of the biophysical and biochemical parameters (Liang, 2005). Due to the lack of onboard calibrators on the GF-1 satellites, vicarious calibration efforts were made by the data operator (the China Centre for Resources Satellite Data and Application, CCRSDA) to conduct a field survey in August 2014 at the Dunhuang calibration site in China, where in situ data were measured and used for radiometric calibrations, resulting in the latest updated coefficients (updated in October 2014, http://www.cresda.com/n16/n1115/n1522/n2103/191962.html).

In general, vicarious calibrations can be challenging because of their labor intensity, high cost, small dynamic range, and spatial coverage, among other factors. To overcome these limitations, cross-calibration approach has been developed using tandem images from a well-calibrated satellite sensor as a reference; this approach has been successfully used in a number of remote-sensing instruments (Chander, Meyer, & Helder, 2004; Dinguirard & Slater, 1999; Liu, Li, Qiao, Liu, & Zhang, 2004; Teillet, Fedosejevs, Thome, & Barker, 2007; Teillet et al., 2001). A simple image-based cross-calibration method has also been proposed by Li et al. (in revision) to cross-calibrate the GF-1 WFV cameras with the rigorously calibrated Landsat-8 Operational Land Imager (OLI) data (Barsi & Markham, 2013; Roy et al., 2014). The successful use of OLI as the reference instrument was partly due to their analogous

* Corresponding author.
E-mail addresses: lian.feng@whu.edu.cn (L. Feng), pxp@whu.edu.cn (X. Pang).

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spectral bands and similar spatial resolutions between WFV (16 m) and OLI (30 m) sensors. In contrast, although the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments (Terra and Aqua) have demonstrated low radiometric calibration errors, remarkable discrepancies in the ground resolutions and band configurations resulted in large calibration uncertainties (20–40%) when they were used as the references data (Li et al., in revision).

The image-based method is based on the assumption that the surface and atmospheric conditions of the target and reference instruments remain unchanged during the <30 min of overpassing time, and the top-of-atmosphere (TOA) signals of the two sensors are identical when the difference in spectral responses is adjusted. Improved radiometric performance has been demonstrated over the first version of the officially released coefficients (released in October 2013, http://www.cresda.com/n16/n1115/n1522/n2103/191340.html).

The assumption for the image-based method may not hold, however, for WFV observations with large view angles. Fig. 1a illustrates the schematic diagram of the footprints of the Landsat-8 OLI and four GF-1 WFV cameras. The images collected by the Landsat-8 OLI are generally at nadir-view, with the largest sensor view zenith angle being ±7° (Song, Woodcock, Seto, Lenney, & Macomber, 2001). In contrast, the range of the view zenith angle for the close-nadir instruments on GF-1 (WFV2 and WFV3) is 0° to 24°, and for the off-nadir instruments (WFV1 and WFV4) the range is 24°–40°. Although such ranges are less than the coarse spatial resolution satellite data (for example, 0–>55° for MODIS and the Visible Infrared Imaging Radiometer Suite (VIIRS)) (Cao, 2013; Vermote, Kotchenova, & Ray, 2011), the view zenith angle of WFVs appear much larger than the Landsat series sensors or other instruments with spatial resolutions of tens of meters.

As simulated using the Second Simulation of the Satellite Signal in the Solar Spectrum model (or 6S) (Vermote, Tanré, Deuzé, Herman, & Morcette, 1997), the increase of the reflectance from the atmospheric path (ρ_{path}) can reach >20% for the off-nadir WFV cameras compared with nadir view ($\rho_{path,\theta=0°}$). Moreover, the difference increases dramatically for larger view zenith angles (say >20°) due to the rapidly increasing distance of the atmospheric path. As such, the unequal atmospheric contributions between the target and reference sensors may lead to relatively large uncertainties when using the image-based cross-calibration method, and this is particularly true for off-nadir instruments. An additional problem associated with different satellite geometry is the anisotropic reflection of the surface targets (Barnsley, Allison, & Lewis, 1997; Franch, Vermote, Sobrino, & Fédèle, 2013; Lucht & Roujean, 2000; Lucht, Schaaf, & Strahler, 2000; Schaaf et al., 2002), which could be more significant for observations with large view angles (Jackson et al., 1990; Meyer, Verstraete, & Pinty, 1995) and could lead to much more pronounced errors in the calibration coefficients.

Fortunately, state-of-the-art algorithms have been developed for MODIS to create standard aerosol and bidirectional reflectance distribution function (BRDF) products (Kaufman et al., 1997; Remer, 2008; Schaaf et al., 2002). Global and regional validations and applications suggest that these products can be safely used to simulate the atmospheric contributions to the satellite signal, as well as the BRDF effects resulting from non-Lambertian surface targets in any viewing direction (Ichoku et al., 2002; Jin et al., 2003; Liang et al., 2002; Remer et al., 2005; Salomon, Schaaf, Strahler, Gao, & Jin, 2006). Thus, the MODIS atmosphere and BRDF products will be used to solve the large view angle-related problems that cannot be handled by the image-based cross-calibration method, from which the calibration accuracy is expected to be improved. The objectives of this study are:

1. To develop a radiative transfer modeling (RTM)-based cross-calibration method for WFV instruments using the Landsat-8 OLI as a reference. In this process, MODIS aerosol products will be used to simulate the atmospheric contributions of both sensors, and MODIS BRDF products will be used to correct the different sun-view geometry between OLI and WFV images; and
2. To estimate the uncertainties of the derived cross-calibration coefficients using both satellite images and in situ data and to discuss the feasibility of the proposed method and the usefulness of the MODIS aerosol and BRDF products.

2. Data selection

2.1. Satellite datasets

Both the GF-1 and the Landsat-8 are in sun-synchronous orbits with a descending node, and their overpass times are similar (~10:30 am local time). Four WFV cameras are onboard the GF-1 satellites with a combined swath of ~800 km. The revisiting period for GF-1 is ~4 days at the equator, which is only 1/4 of that for Landsat (16 days), enabling detection of short-term changes in land surface features. Four spectral bands covering visible to NIR spectral ranges are configured in the GF-1 WFV instruments, which are quantified over 10-bit digital numbers (DN). Analogous Landsat-8 OLI bands can be found for each WFV wavelength, except for a wider bandwidth in the NIR band of the WFV. A more detailed comparison of configurations (such as wavelengths, spectral responses, etc.) between the GF-1 WFV cameras and the Landsat-8 OLI is shown in Li et al. (in revision).

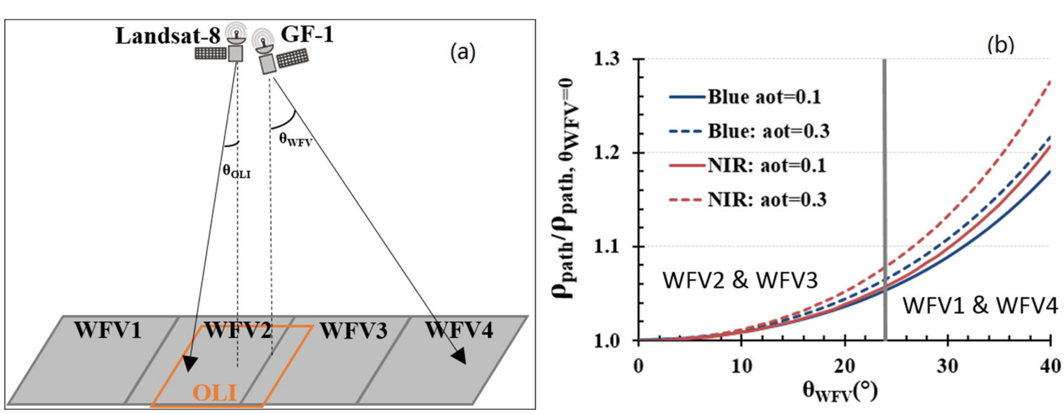

Fig. 1. (a) The schematic diagram to show the positions of the Landsat-8 and GF-1 satellites and the footprints of the OLI and WFV cameras. The WFV1 and WFV4 are off-nadir instruments, and the WFV2 and WFV3 are close-nadir instruments. (b) The ratio between simulated reflectance of atmospheric path at different sensor zenith angles to that of the nadir view (zenith angle = 0°), the results for blue and NIR bands with clear ($aot_{550\ nm}$ = 0.1) and turbid ($aot_{550\ nm}$ = 0.3) aerosol conditions are plotted. The gray bar indicates the lower bound of the sensor zenith angle of the off-nadir instruments, which is also the upper bound of the two close-nadir cameras. θ_{OLI} and θ_{WFV} are view zenith angle of Landsat-8 OLI and WFV cameras, respectively.