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Supervised vicarious calibration (SVC) of hyperspectral remote-sensing data

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ABSTRACT

A full-chain process approach to extracting reflectance information from hyperspectral (HRS) data which is valid for all sensor qualities is proposed. This method is based on a mission-by-mission approach, followed by a unique vicarious calibration stage. As the HRS sensor's performance may vary in time and space, a vicarious calibration method to retrieve accurate at-sensor radiance values is necessary. In fact, vicarious calibration solutions usually rely on natural, well-known, bright and dark targets that are large in size and radiometrically homogeneous. Since such targets are not commonly found in the field for every mission and their spectral features can sometimes resemble artifacts in the corrected radiance, a new vicarious calibration approach is needed. This paper describes a new method that uses artificial agricultural black polyethylene nets of various densities as vicarious calibration targets that are set up along the airplane's trajectory (preferably near the airfield). The different densities of the nets combined with any bright background afford full coverage of the sensor's dynamic range. We show that these artificial targets can be used to assess data quality and correct at-sensor radiance within a short time. Several case studies are presented using Aisa-DUAL sensor data taken at different times from different locations. We found that even "lost data" (in terms of radiance drift) could be recovered by the suggested method. We term the suggested vicarious calibration approach supervised vicarious calibration (SVC) and demonstrate its performance in terms of spectral accuracy. The limitations of the method are also discussed but the overall conclusion is that the suggested procedure is functional, valuable and practical for sensors with questionable or uncertain laboratory-determined radiometric parameters.

1. Introduction

In the early 1980s, the concept of imaging spectrometry (IS), or hyperspectral remote sensing (HRS) of the Earth was demonstrated by NASA JPL using AIS, the first airborne HRS sensor (Goetz et al., 1985). Since then, many sensors have been developed and many users are taking advantage of this promising technology for a variety of applications (Goetz, 2009). One of the major advantages of the HRS technique is the extraction of reflectance properties from every pixel within an image in a large number of narrow spectral bands. This new information enables detailed and quantitative analysis of every pixel within the image.

Accurate radiometric values are the key factor in the extraction of quantitative information based on spectral reflectance from at-sensor radiance. Nevertheless, when the onboard digital numbers (DNs) are incorrectly converted to radiance values, the subsequent normal chain of processing of the HRS data might be interfered with, resulting in errors in the final classification. In general, the quality of HRS sensors varies from very high to moderate (and even very poor) in terms of signal-to-noise ratio, radiometric accuracy and sensor stability. In general, sensors deteriorate radiometrically in time and space and thus require periodic calibration. Airborne sensors periodically undergo routine calibrations in the laboratory (Dinguirard & Slater, 1999; Slater et al., 1987). However, some HRS sensors, particularly those of low stability, may not hold the radiometric parameters as evaluated in the laboratory and thus the conversion of DNs to radiometric units might fail (Secker et al., 2001). Instability of the sensors' radiometric performance might be caused by either known or unknown factors encountered during sensor transport, installation and/or even data acquisition. As part of data rectification towards achieving actual radiometric values, these distortions have to be assessed and quantified for each mission.

Vicarious calibration methods that attempt to solve local aspects of sensor instability use well-known ground targets, which are measured during (or close in time to) the sensor overpass (Bruegge et al., 2004; Green et al., 1996; Pearlman, 2003; Robert & Kaufman, 1986; Secker et al., 2001; Vermote & Kaufman, 1995; Yoshida et al., 2005). The vicarious calibration targets that rely on the empirical line (EL) assumption (Conel et al., 1987) should be spectrally known and stable, least affected by the atmosphere, located near the area of interest (AOI), and should cover a large area and range of albedo (Ballew, 1975; Elvidge, 1988; Kruse et al., 1990, 1992, 1993; Roberts et al., 1985, 1986; Smith & Milton, 1999). They also have to be spectrally featureless, stable and homogeneous, easy to maintain and access, and well

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documented for every mission. Meeting the foregoing requirements for every airborne HRS campaign is seldom, if ever, possible.

Over the past six years, we have operated the airborne Aisa-DUAL HRS sensor over many landscapes. During this time, we have encountered problems with the quality of the radiometric output which might be related to radiometric-sensor instability. This obstacle has prevented the forward use of model-based atmospheric correction methods (e.g. ATCOR-4, ACORN) to generate reflectance information from every pixel within the image. Further, it has been shown that in some cases, even the EL method cannot retrieve reliable reflectance information. Current missions are spread out all over the country and cannot make use of the (inter)national calibration site, Makhtesh Ramon (Ben-Dor, 2009), which is situated far from the mission locations. Accordingly, a new approach for vicarious calibration was developed and examined to meet the aforementioned requirements of the vicarious calibration targets. The purpose of the present paper is to report the results of this supervised approach for vicarious calibration at any location/time and under any atmospheric conditions for airborne HRS sensors.

2. Methodology

2.1. Generalities

The proposed approach is based on allocating, operating and constructing a portable well-characterized artificial calibration site within the trajectory of the aircraft, analogous to the MTF (modular transfer function) spatial/geometric calibration approach (Justice et al., 1989), but for radiance calibration. The criteria for setting the proposed vicarious calibration targets are: 1. the target must maintain a large dynamic radiometric range encompassing the range of brightness values on the mission, and it should be stable in time and space; 2. it should consist of spectral features that are linearly correlated to the albedo intensity; 3. if non-permanent, the artificial calibration target should be easy to transport, and simple to install and measure under (almost) any conditions; 4. the required size of each target has to be at least 50 pixels, with the target's long side being placed along the flight path. A suitable product that satisfies the aforementioned requirements is the artificial black polyethylene netting commonly used in agriculture as a cover to shade greenhouses from direct sun radiation in arid climates. These nets (Exxon Mobil, metallocene-based polyethylene resin nets) are dark, have no absorption features across the entire spectral region (VIS-NIR-SWIR), and are manufactured in different densities. The densities available at the factory are 13%, 17% and 25%, but more densities can be obtained by laying several nets together. The nets weigh ~0.001 kg/m^2, are easy to fold and transport and cost about \$2/m^2. The nets can be spread over a bright target surface (e.g. gravel lot or sand dune), providing an albedo sequence from the bright background to the darkest net (100% density). If the background has spectral features (e.g. in the case of a calcareous site), the decay of the absorption features of the calcite (around 2300 nm) in the background by the dark featureless net is linearly correlated to the albedo sequence (governed by the net density). This guarantees that no absorption artifacts (of the background) will remain in the atmospherically corrected image (Aspinall et al., 2002; Smith & Milton, 1999).

The density set in this study consisted of approx. 0%, 13%, 17%, 25%, 50% and 90%, where for each density the net was 15 m × 40 m, weighed from 4 to 15 kg and had a volume of about 0.5 to 1 m^3. The main concept of the method is to allocate a bright area near the flight trajectory, and unroll the nets just before the aircraft takes off. After measuring reflectance and radiance (during or close to the overpass) and acquiring airborne data, the nets are refolded and stored. The main advantage of the albedo sequence is that the calibration targets maintain stable spectral accuracy (of the background) with different radiometric responses (from the net covers). These properties enable better modeling of the sensor's radiometric behavior.

The important stage is thus choosing a suitably bright background target and location, preferably a flat bright area of 300 × 300 m size such as: light concrete, light soil (without organic matter), calcite (surface rich in calcium carbonate) or limestone (gravel), dune sand, etc. The preparation of the calibration site for a mission takes between 25 and 30 min. Using the suggested procedure, we were able to exploit the targets for vicarious calibration and to extract parameters that would confirm the radiometric accuracy (quality assurance, QA, using quality indicators, QI) of the sensor, and if necessary, to generate a new set of parameters to rectify the sensor's actual values. A concrete assumption for this approach is that the new set of spectral/radiometric coefficients is suitable for a concurrent mission run on the same operational date as long as the sensor remains stable throughout the mission period (same gain, integrative time and frame rate of the sensor).

2.2. Spectral measurements

The ground spectra of the supervised vicarious calibration (SVC) targets were measured with the portable field spectrometer ASD Field SpecPRO (Analytical Spectral Device, Boulder, CO) which consists of 2151 wavelengths ranging between 350 and 2500 nm, with band widths of 2 nm in the VNIR region (350–1050 nm) and 10 nm in SWIR region (1050–2500 nm), and wavelength accuracy of ±1 nm/±0.1 nm. Each ground target (the nets, the background surface and the targets to be validated) was measured by averaging 40 spectra of both radiance and reflectance values during the overpass. The reflectance mode was calibrated against a Spectralon® white reference panel. The optimization procedure was programmed to work in both radiance and reflectance modes, averaging 40 replications per measured spectrum. Each target was measured systematically by collecting about 40 points along the net's area while keeping every point to be measured in the same position relative to the sun. All points in a designed matrix were about 3 m distant from each other and the spectral measurement was taken from 1 m height with a bare-optics of a 24° field of view (FOV) (about 60 cm^2 footprint) with spectral error (standard deviation) between 0.1% and 1.0%. All spectra were averaged to yield a single mean corrected spectrum for each of the net targets, which were later re-sampled to the sensor spectral configuration (band position and full width at half-maximum FWHM).

2.3. Calibration theory

The at-sensor measured radiance is given in Eq. (1) for every wavelength:

$$Ls = \tau\rho Eo/\pi + Lpath \tag{1}$$

where Eo is the sun's radiance above the atmosphere at a certain zenith angle, τ is the atmospheric transmittance, ρ is the surface reflectance and Lpath is the selective scattering (Rayleigh and Mie) contribution to the sensor output.

Assuming that during the operation, the sensor holds the calibration coefficients that were generated in the laboratory during the system calibration stage, Eq. (1) is valid as is. In the case of a non-calibrated sensor (or drift from the laboratory calibration), the achieved at-sensor radiance (Ls) is a product of the “real” radiance multiplied by gain and offset coefficients that adjust the miscalibrated laboratory information to at-sensor radiance as follows:

$$Ls = \{L(\mathrm{gain})[\tau\rho Eo/\pi + L(\mathrm{path})]\} + L(\mathrm{offset}) \tag{2}$$

where L(offset) is the unknown noise that enters the sensor from the time of the last laboratory calibration and L(gain) is an amplification factor that depends on the sensor's functionality and surrounding condition that drifts from the laboratory calibration process.

If the laboratory calibration holds, L(gain) = 1 and L(offset) = 0; this is a well-calibrated sensor and Eq. (1) is valid. However, not all sensors