Recent Progress in In-Flight Radiometric Calibration and Validation of the RapidEye Constellation of 5 Multispectral Remote Sensing Satellites

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Abstract. BlackBridge AG is a geospatial data provider which operates a constellation of five identical multispectral remote sensing satellites. These satellites cover five spectral bands in the visible (VIS) and near infrared (NIR) spectral range. Radiometric calibration of multispectral and hyperspectral instruments like those operated by BlackBridge AG is of fundamental importance if the data e.g. should be used for remote sensing applications or if the atmospheric influence to the data should be corrected using methods based on atmospheric transfer codes. For the RapidEye constellation three goals are achieved using calibration. First, spatial calibration corrects response differences for the individual CCD elements in one CCD array. Second, temporal calibration provides a comparable measurement of the five different cameras over time. Finally, absolute calibration links the relative digital number (DN) outputs of the sensors to absolute at-sensor radiance levels.

This paper explains in detail the methodologies used for radiometric calibration of the five satellite constellation.

1 Introduction

To extract reliable information from remote sensing imagery they need to be corrected for systematic defects or undesirable sensor characteristics [1].

The level of the calibration necessary is highly dependent on the intended application of the data. If the data is envisaged for a visual inspection or interpretation a correction for the pixel response non uniformity (PRNU) is most important to make the detector response equal when exposed to the same amount of light. In addition to the PRNU correction most applications like time series analysis or automatic change detection [2] rely on a very stable data quality and accuracy over time. For the application of physically based atmospheric correction models like MODTRAN [3,4] an absolute calibration of the data is essential.

The RapidEye system initially was designed to support accurate and automated analysis of vegetated areas. Such targets usually require the detection of

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very subtle spectral features and in consequence a very accurate correction and calibration of the multispectral satellite data.

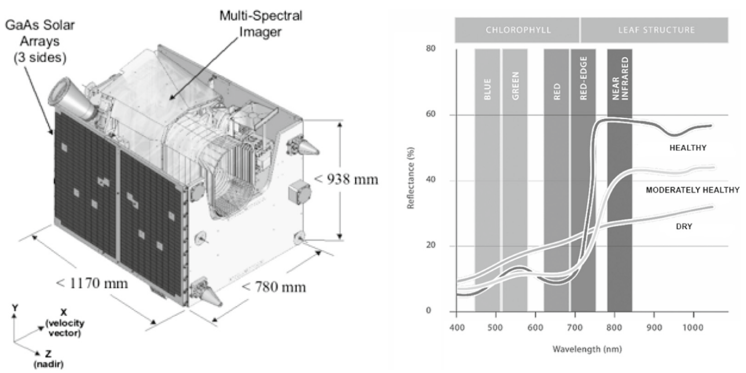
The initial radiometric calibration concept [5] planned statistics based methods for on-orbit PRNU correction and temporal calibration after a pre-launch calibration and characterization phase. In the course of the operation of the system, the calibration methods have been adjusted significantly to reflect the actual needs of the customers. Finally, absolute calibration using the reflectance based vicarious calibration method [6,7] has been added to the calibration process and applied successfully for several years [8].

2 The RapidEye Constellation of Satellites

RapidEye is a full end-to-end commercial Earth Observation system comprising a constellation of five satellites carrying identical multispectral cameras and their dedicated spacecraft control and data processing centres. The system is owned and operated by BlackBridge AG.

The constellation of satellites was launched into orbit on August 29, 2008 from Baikonur Cosmodrome on one Dnepr launch rocket and injected into a sun synchronous orbit at a nominal altitude of 630 km and an inclination of 97.9°. The spacecraft follow each other in their orbital plane at about 19 min intervals. These orbital characteristics allow the system to image any place on earth between ±84° daily with a satellite roll angle up to ±20°.

The satellite platform is a Micro Satellite platform developed and built by Surrey Satellite Technology (SSTL) (Fig. 1(a)). The multispectral imager (MSI) observes the Earth in five discrete spectral bands. The instrument is composed of an all-reflective three mirror anastigmat telescope that is mounted on a thermally controlled optical bench, and a focal-plane assembly (FPA) containing five linear CCD arrays, each integrated with a dichroic filter to provide spectral separation into discrete bands [8] (Fig. 1(b)).



(a) Satellite (b) RapidEye Bandset

Fig. 1. RapidEye satellite bus sketch (left) and RapidEye band sets (right)

The shown bandset is mainly adjusted for applications of vegetation analysis like agriculture and forestry. The RapidEye constellation carries the first multispectral imagers containing Red-Edge bands, which are especially useful for detecting subtle differences in the health status of plants. Figure 1(b) emphasizes the usefullness of the Red-Edge band as it helps to characterize the difference between healthy green vegetation and vegetation showing an already reduced vitality.

The native spatial resolution of 6.5 m at nadir, together with a broad swath width of 75 km and the imaging capacity of up to 1 500 km per orbit, results in a total of up to 6 million sqkm of high quality and high resolution remote sensing imagery per day. As of 2015 the growing image archive owned by BlackBridge holds more than 6 billion sqkm of imagery.

3 Calibration of the Cameras

The radiometric calibration of the RapidEye Constellation is broken into three different calibration goals, each performed following distinct methods and procedures. These methods are:

- Spatial Calibration
- Temporal Calibration
- Absolute Calibration

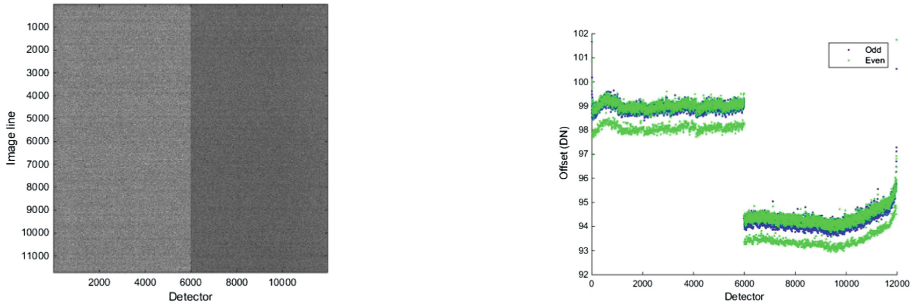
These methods are described in the following section.

3.1 Spatial Calibration

The purpose of spatial calibration is to maintain homogeneous spectral responses among all of the 12 000 CCD detectors in each of the five spectral bands of the five RapidEye satellites. Visually this calibration step prevents from visible banding and striping effects in the imagery. To adjust the individual sensor responses to each other, the detectors are assigned with individual gain and offset values, resulting in one radiometric correction table (RCT) per band containing 12 000 offset and 12 000 gain values.

At the beginning of operations for this purpose a purely statistical method has been used. This method used the detector mean and standard deviation values of all operational images to calculate the correction values. As for this method imagery worth of sometimes several weeks have been necessary to create useful correction values a new method has been adopted.

With this side slither method the correction factors are obtained by evaluating two special types of images, dark shots and side slither images, which are acquired by every satellite every three months [9]. The update resulting from the quarterly dark shots and side slither images is performed as a regular maintenance measure even if there is no apparent quality issue. In case of sudden detector changes, which can occur for various non-critical reasons, the offsets can be taken from the latest available dark shot and the gains can be derived statistically from the latest operational imagery, overlaid with the last (up to three months old) side slither gains. Hence, this eliminates the need for special acquisitions during fast troubleshooting.



(a) Dark Shot over the Pacific Ocean

(b) Derived Detector Offsets, Separated for Odd and Even Detector Numbers

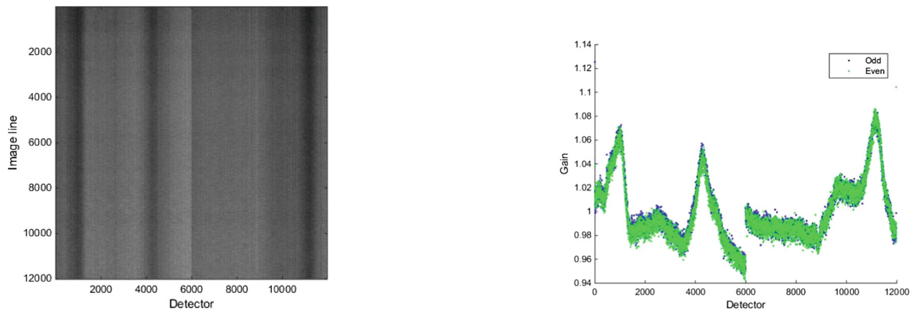
Fig. 2. Calculation of the detector offsets using a dark shot.

A dark shot, as seen in Fig. 2(a), is acquired over the Pacific Ocean at night and is used to calculate the detector offsets. The offsets are the detectors' response to a zero input. As blinding the detectors is not possible, a zero input image is simulated by a dark shot. Figure 2(b) shows the calculated offsets, which correspond to the detector-wise (column) means of the dark shot data. The difference between the left and the right sides of the detector means is due to the readout mechanism used on-board.

A side slither image, as seen in Fig. 3(a), is acquired over a bright homogeneous target while the satellite is yawing by 90° and allows for the calculation of the detector gains. During northern hemisphere summer time, side slither images are acquired over Greenland, whereas during southern hemisphere summer time the target area is Dome C in Antarctica. The premise behind a 90° yawed image is that each detector captures the same spot on the ground, which allows for a comparison of the detectors' responses to the exact same incoming radiation. It is desirable to have as bright a target as possible since the differences in detector gain become more apparent at the high end of the response curve. Figure 3 shows a small extract from a (shifted) side slither and the resulting detector gains.

To obtain the detector gains the individual detector responses are shifted to align the ground samples. Following this, the previously calculated detector offsets are subtracted from the corresponding column and the remaining detector (column) means are divided by the overall side slither image mean, resulting in the detector gains shown in Fig. 3(b).

These gains and offsets must be adjusted before they meet the form needed for the RapidEye RCTs. This adjustment is briefly explained at the end of this section. However, there is a second way to calculate the detector gains, used



(a) Extract from a Shifted Side Slither over Greenland

(b) Derived Detector Gains, Separated for Odd and Even Detector Numbers

Fig. 3. Calculation of the detector gains using a side slither.

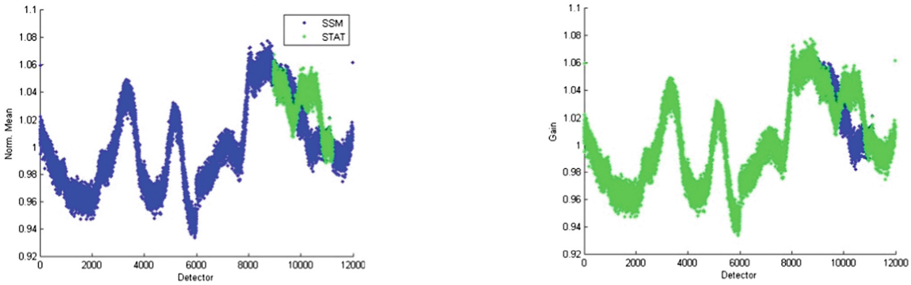
especially in cases of sudden detector changes and gradual changes over time. In those cases it is not feasible to perform a side slither maneuver every few days.

Sudden detector changes usually affect only a few thousand detectors and become visible as a banding in the imagery. As the sudden change leaves the rest of the detectors unaltered, only the gains of the affected detectors need to be updated. The detector offsets can be taken from the last quarterly update and the detector gains for the affected detectors are derived from statistics of the most recent operational imagery. It is assumed that data taken during a side slither maneuver provides the most accurate detector gains, which is why those are kept for the unaffected detectors. This combination method finds the affected detectors, uses statistics collected after the sudden detector change to estimate new gains for these detectors, and combines the new gains for the affected detectors with the previous side slither gains for the unaffected detectors.

During normal operation, the detector means of every acquired image are stored. For the combination method, those stored means are retrieved for a period of at least one week, starting after the sudden detector change.

Figure 4(a) shows the latest side slither gains compared to the gains derived from the statistics of the detector means. The statistical gains are only displayed roughly between detectors 9 000 and 11 000, which is where the sudden detector change took affect. The exact location of the banding is determined by the zero crossing points of the difference of two curves fitted to the side slither and the statistical gains for 12 000 detectors each. Two individual bandings which are separated by less then 1 000 detectors are treated as one. In order to blend the statistical gains into the side slither gains, a buffer of 500 detectors on either side of the banding is used to guarantee a smooth transition between the two datasets.

The final combined gains for the 12 000 detectors, which are valid after the sudden detector change, are displayed in Fig. 4(b). They equal the last side slither gains anywhere which is further than 500 detectors away from the banding, equal



(a) Side Slither Gains with Adjusted and Merged Statistical Gains

(b) Combined Side Slither and Adjusted Statistical Gains

Fig. 4. Collecting and merging the side slither gains and the statistical gains

the statistically derived gains within the banding and form a smooth transition between both datasets in the 500 detector wide buffer on either side of the banding.

As a last step, the gain and offset values have to be adjusted to be applicable to the RapidEye data. The hitherto calculated gains and offsets correct the preprocessed input signal Q as follows,

$$Q'_i = (Q_i - o_i) \cdot g_i \ , \tag{1}$$

where Q' is the corrected digital signal, o is the offset, g is the gain and the identifier $i \in \{1, \ldots, 12\,000\}$ denotes the individual detectors. Before filling out the RCTs that are applied to the RapidEye data, the gains and offsets are adjusted to correct Q in the following way

$$R = (Q_i \cdot g'_i) - o'_i, \tag{2}$$

where R is the corrected signal in DNs, o' is the adjusted offset, g' is the adjusted gain and i is as above.

3.2 Temporal Calibration

The objective of the temporal radiometric calibration is to achieve homogenous sensor responses between all five satellites of the constellation over the entire mission time. This is impaired by a degradation of sensitivity of the sensors. The degradation mainly depends on the quality of the assembled components and their life-time, but can be also affected by certain incidents like overblending. The temporal calibration tries to figure out the magnitude of this degradation. So as a result of this, adjustment-parameters can be applied.

This procedure is performed for all five bands on each satellite. This allows BlackBridge to generate image-products with comparable radiance since the start of operations and to ensure high radiometric quality for all products.

To evaluate the degradation of a sensor BlackBridge uses a network of 27 pseudo-invariant calibration-sites all over the world. An overview of these sites is given in Fig. 5. The sites have a size of about 50 × 200 km each and cover approximately 20 to 30 RapidEye-Product-tiles per site. All calibration-sites are located in areas with a stable and dry surface, essentially deserts.

Each calibration-site is scheduled for acquisition every fourteen days. The acquisition of these was started at the beginning of the mission and meanwhile more than 300 000 RE-tiles have been acquired for calibration purposes.

Based on this amount of imagery, statistical means are calculated for certain points in time. The assumption behind this calculation is that mean values of a set of images covering pseudo-invariant calibration-sites are stable over time and will be only affected by a sensitivity decrease of the sensor. So, from the behavior of these mean values the degradation of the sensor can be derived.

To ensure that the changing mean reflects only the degradation, all unsuitable images, that contain blackfill, clouds, haze, snow etc., must be excluded from the calculations. This is done by an incremental filtering process that sorts all inappropriate images out. In a first step all acquisitions of a single tile-id are filtered against their mean, then the remaining tiles of a single calibration-site are filtered against their mean and finally all sites are filtered together. The benchmark for filtering is always the current mean value of the section and its standard deviation.

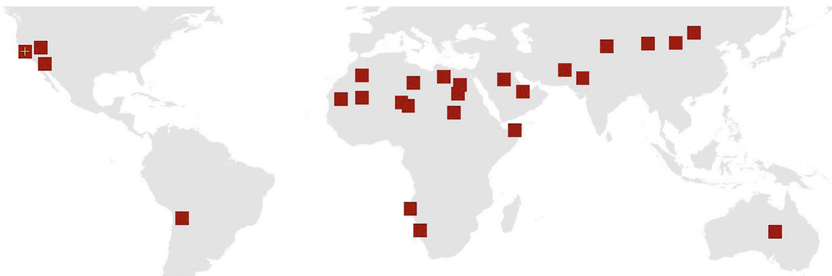


Fig. 5. BlackBridge calibration sites

Since all images in the database are affected by previously applied radiometric correction parameters, the image-means must be reduced to normalized values. This step is done before the filtering process starts.

In addition to this the images show seasonal differences. These are visible in larger mean values between April and September and smaller means between October and March. The reason for this is that the majority of the calibration-sites are located in the Northern hemisphere. Therefore, the filtering process and data-analysis is applied only on intervals of multiples of 12 months.

After all filtering a line is fitted through all remaining mean-values, where the gain of the line shows the degradation with respect to time. This gain is called “DailyTemporalFactor (T)”.

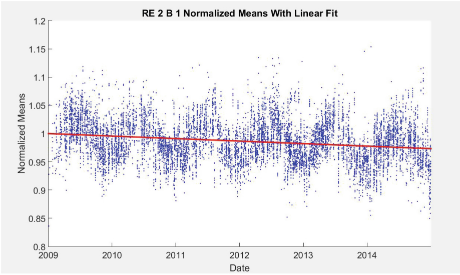


Fig. 6. Linear fit of tile means for RE2B1

Figure 6 shows an example of the result of the filtering process and the line-fit for RE2 Band1.

In addition to this continuous, but small, degradation for some of the sensors an abrupt decline in sensitivity was found. This can happen after special events, like down-time for a satellite. Knowing an event has occurred, the sensor-sensitivity before and after the event is analyzed in detail, to determine, whether a discontinuity occured. If so a Temporal Discontinuity Factor (D) is calculated as:

$$D = \frac{(T_{before\ event} - T_{after\ event})}{T_{after\ event}}$$

To keep the sensor responses over time constant the DailyTemporalFactor (T) and the TemporalDiscontinuityFactor (D) are applied on all images. T as a daily factor is multiplied by the number of days between image acquisition and system commissioning. D is applied as constant factor for all images that are taken after the date of the discontinuity.

Finally, the sensor-degradation for all five RapidEye satellites are displayed as a decline in percentage since mission start. The current values from the end of July 2015 can be seen in Fig. 7.

The maximum value for degradation is nearly 5 % for RE1 Band1. With respect to seven years mission operations, this is a very respectable status. The numbers have a bit-depth of 16 bit, unsigned.

3.3 Absolute Calibration

Absolute calibration means to convert the digital counts provided by the camera into physical radiance units. This procedure is essential for a wide variety of applications.

Usually the instruments are characterized and calibrated very accurately before integration with the spacecraft and launch into the Earth's orbit. During the assembly and mostly the launch but also during the whole mission lifetime the spectral characteristics of the instruments including the detector sensitivity is not completely stable. This sensor behaviour requires a proper validation and calibration throughout the full mission lifetime.

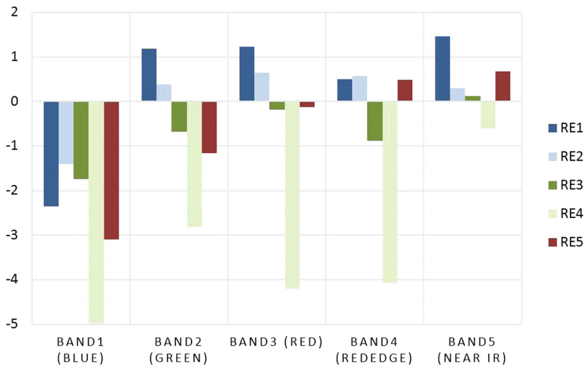


Fig. 7. Degradation [%] of RE-sensors July 2015

In the calibration and validation community many different methods are used to achieve the goal of an absolutely calibrated satellite. For the Landsat 8 Operational Land Imager the calibration teams are using on-board calibration equipment like lamps, solar diffusors or shutter doors, celestial objects like the moon [10] or ground based vicarious calibration [11].

For commercial and small satellite programs it is usually not practically feasible to integrate on-board calibration equipment or use celestial objects. Therefore, BlackBridge uses a reflectance based vicarious calibration approach for absolute calibration.

The reflectance based vicarious calibration methodology relies on ground-based surface reflectance measurements of a selected site and atmospheric conditions over that site [12]. The ideal sites for vicarious calibration activities show a homogeneous surface and a stable atmosphere with as little scatterers as possible. Therefore the ideal sites are high elevation flat desert areas. However, such sites are usually very bright and the effort to access them is high. Hence other sites like pastures are used successfully for vicarious calibration, too [7].

For the RapidEye satellites BlackBridge AG has maintained support contracts with the College of Optical Sciences, University of Arizona (UoA) since 2009. UoA is using the very bright Railroad Valley site [13] (Fig. 8(a)) as a ground target. To achieve a proper absolute calibration over as wide a dynamic range as possible a further contract with the Image Processing Lab of the South dakota State University (SDSU) has been added in 2013. SDSU uses a pasture site which is, compared to the RRV site, significantly darker at least in the visible bands (Brookings 3M site) [14] (Fig. 8(b)).

In addition to the manned site at Railroad Valley, an automated Radiometric Calibration Test Site (RadCaTS) has been used since 2015 [15]. Table 1 summarizes the yearly volumes of the simultaneous field and image collects.

Since 2011 the reference information has been collected for all 5 RapidEye sensors, while in 2009 and 2010 only 2 sensors were used. To characterize the full

(a) Railroad Valley Calibration site (b) Brookings Calibration site

Fig. 8. Used calibration sites

Table 1. Number of collects since 2009

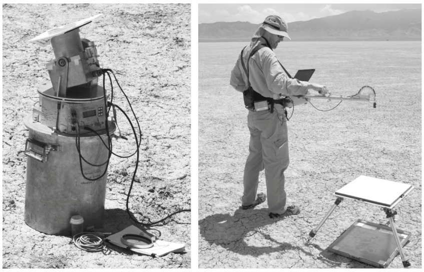
	Railroad Valley	Brookings
2009 - 2010	10	-
2011	5	-
2012	25	-
2013	5	9
2014	10	12
2015 *	105**	10

* expected; ** incl. RadCaTS

constellation after these two initial years the statistics based temporal calibration approach was used to extend and supplement the absolute calibration to the other sensors.

The vicarious calibration process measures the hyperspectral upwelling radiance using a field spectrometer (Fig. 9(b)) simultaneously with the satellite overpass. In addition, the atmospheric transmittance is measured in the interval surrounding the overpass (Fig. 9(a)). Extinction values, calculated from the atmospheric transmittance measurements, together with the overpass geometry information is used to support the transformation of the hyperspectral top of canopy reflectance data into at-sensor radiance. After the accurate resampling of the hyperspectral data to the actual sensor spectral response this simulated at-sensor radiance is compared to the satellite measured at-sensor radiance. The differences between the simulated and satellite measurements from all references on both of the sites are used to calculate adjusted gain and offset values for a linear correction of the satellite measurements to reflect absolute radiance measurements in the RapidEye products.

The current settings of these linear correction parameters reflect the results of all reference measurements until the end of 2014. With these measurements the remote sensing data is in sync in an absolute manner. The new measurements from 2015 will be incorporated as soon as they are available as a whole. This is expected to be early 2016.



(a) Sun Photometer (b) Field Spectrometer

Fig. 9. Measurement devices

3.4 Conclusion and Outlook

The methods described above are showing a distinct improvement in accuracy and responsiveness compared to the methods initially designed for the constellation of the satellites. The side slither method described in Sect. 3.1 makes it possible to take corrective action right after response changes of a group of detectors have been detected. Additionally the result of the flat fielding using this method is visually clearly better than those using the original statistical method. With the addition of the dark Brookings calibration site to the absolute calibration an improvement in accuracy especially in the darker regions could be achieved.

For the next update taking place in 2016 it is planned to add another darker water site to achieve a further improvement in the dark region of the dynamic range especially for the red-edge and NIR bands.

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