THE CALIBRATION PROCEDURE OF THE MULTISPECTRAL IMAGING INSTRUMENTS ON BOARD THE RAPIDEYE™ REMOTE SENSING SATELLITES

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ABSTRACT:

RapidEye operates five spacecraft within a constellation. Each spacecraft accommodates an identical multispectral pushbroom imager as the payload. RapidEye has the capability to view any place on Earth and capture up to 4 million km^2 of image data on a daily basis. The key business interests of RapidEye are agricultural and cartographic products and services, however, the advantages of the RapidEye System are widespread over various thematic applications (e.g. pipeline monitoring, medium scale mapping, disaster monitoring and many others). To maximise the systems capabilities, all five instruments have to have the same radiometric response behavior and the same geometric properties.
To achieve this goal, RapidEye applies a dedicated calibration concept to optimize the spectral and geometric homogeneity across all the imagers over the foreseen mission lifetime. This will be achieved by a spatial and a temporal calibration for the radiometric corrections and geometric adjustments using both camera alignment and scale calibration and camera focal plane calibration. This paper mainly describes the concepts used for the relative and absolute radiometric calibration of the five multispectral imagers but also briefly describes the geometric part of the calibration.

1 INTRODUCTION

RapidEye is a provider of high resolution remote sensing imaging data. Located in Brandenburg an der Havel, Germany, just west of Berlin, RapidEye operates 5 identical small spacecrafts being equally spaced in a sun synchronous low earth orbit (LEO). Each spacecraft accommodates the same pushbroom-style, multispectral imager (MSI) collecting data in five discrete bands of the electromagnetic spectrum at a generic spatial resolution of 6.5 m at nadir. Launched in August, 2008 and in commercial operation since early 2009 the constellation is capable of acquiring and downloading over 4 million km^2 of high resolution, multispectral imagery per day, and has the ability to collect data from any point on Earth every day. The technical characteristics of the RapidEye multispectral imagers are given below in Table 1.

Spectral bands	Blue (0.44 - 0.51 μm) Green (0.52 - 0.59 μm) Red (0.63 - 0.69 μm) Red Edge (0.69 - 0.73 μm) Near IR (0.76 - 0.85 μm)
Ground Sampling Distance	6.5 meters
Dynamic Range	12 bits
Altitude	630 km

Table 1: *technical characteristics of the RapidEye multispectral imagers*

2 THE RAPIDEYE CALIBRATION CONCEPT

The overall calibration of RapidEye data covers two different thematic parts:

- the radiometric calibration which is subdivided into relative spatial, relative temporal and absolute vicarious calibration

and

- the geometric calibration

All the required calibration processes are being executed during three phases, which are described in Section 2.1. Section 2.2 focuses on the geometric calibration while Section 2.3 gives a detailed description of the radiometric calibration approach.

2.1 RapidEye calibration phases

The RapidEye calibration concept consists of the following three phases:

Pre-Launch Calibration: comprised of the initial determination of absolute calibration values, spectral and geometric properties, and thermal correction factors resulting from the ground testing campaign. The knowledge of the instrument behavior and the trend of the radiometric responsiveness of the different spectral bands is based on laboratory calibration using calibrated light sources. During this phase the initial on-board gain and offset tables were generated. The on-ground gain and offset tables were also prepared, containing only the values 1 (gain) and 0 (offset).
Initial Post-Launch Calibration: comprised of ground target based radiometric and geometrical calibration of the payloads during the system commisioning and calibration phase just after launch of the satellites. The correlation between initial inflight calibration and the pre-launch calibration dataset was established by evaluating an increasing amount of statistical data derived from acquired imagery. This allows the observation and correction of any effect(s) related to on-orbit changes, resulting in an update of both, on-board and on-ground gain and offset tables as well as in the anticipated finalization of the geometric calibration. The updated on-board gain and offset tables were uploaded to the spacecraft substituting the no longer valid pre-launch tables, whereas the updated on-ground gain and offset tables were

made available within the data processing chain. During this calibration phase MTF and NER validation of the imagers took place.
Periodic In-Flight Calibrations: Periodically the continuously collected statistical data for the radiometric calibration are compared with the calibration baseline. If required, appropriate gain and offset corrections are performed and the updated gain and offset tables are loaded for use on-board and on-ground.

Figure 1 gives a summary of the RapidEye calibration phases.

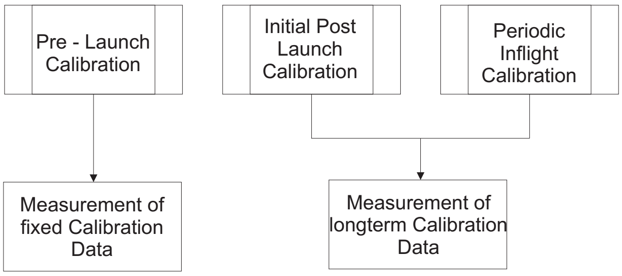

Figure 1: *RapidEye calibration phases*

For the nominal operation of the RapidEye system only the Periodic Radiometric In-Flight Calibration is of importance. The geometric calibration has been finalized during the Initial Post-Launch Calibration phase prior to the beginning of regular operations. After that phase the geometric calibration accuracy is monitored using the GCP marking accuracy database in the ground processing system. If deemed necessary from the analysis of these values the geometric calibration parameters will be updated accordingly.
The methods used for this Periodic In-Flight Calibration are detailed in Section 2.3.

2.2 The Geometric Calibration Approach

Every operational sensor exhibits perturbations relative to the ideal sensor model. These perturbations are caused by optical distortions, thermal related distortions of the focal plane or alignment tolerances. These perturbations require a correction to be applied to obtain the correct position for each pixel .

The geometric calibration of a sensor is necessary in particular to:

- assess and update the initial post-launch geometric calibration which could have been affected by the launch,
- refine the initial covariance estimates which are used to set the a priori weighting factors (to the attitude, ephemeris and GCPs) applied by the Kalman Filter used within the precision modeling software,
- improve the automatic GCP marking performance by removing all systematic model error biases due to alignment errors between the attitude sensors and the camera, errors in scale and geometric distortions such as smile and smirk,
- and, finally, generate accurate image and DEM products.

The initial correction vector for each pixel position is determined by tests during the Pre-Launch Calibration phase. The applied correction approach derives the corrections in form of shifts on the focal plane. Figure 2 shows the ideal sensor in a solid line, while the corrected detector shape is shown in a displaced and

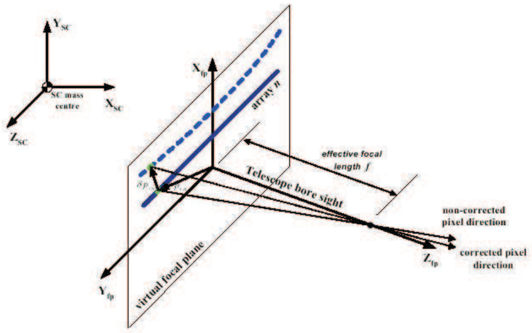

Figure 2: *Sketch of the ideal sensor (solid line) and corrected detector shape (dashed line).*

curved dashed line.
The focal plane distortions, due to manufacturing imperfection and to expected thermal variations of the focal plane, are, as mentioned, measured only pre-launch in the laboratory.
For RapidEye's sensors we perform two different parts of geometrical calibration:

- the camera alignment and scale calibration and
- the focal plane calibration (optical distortion calibration).

The camera alignment and scale calibration produces an updated orientation matrix and effective focal length, while the focal plane calibration produces an updated focal plane pixel projection map.

2.2.1 Camera Alignment and Scale Calibration

The basis for the camera alignment and scale calibration is statistical data, which is derived by assessing the uncertainty of the ground control points (GCPs) which will be used during the geolocation process of the imagery data. Image line/pixel and GCP lat/long/height are recorded for every used GCP (across and along track angular errors). These statistics are gathered in a dedicated, so called Marked GCP Database. With the across track and along track angular error statistics, averaged on a global basis for each calibration period, it is possible to calculate average delta-roll, delta-pitch and delta-yaw biases as well as an average delta scale bias. This allows the adjustment of the camera to attitude, solve the reference coordinate system alignment matrix and adjust the focal length values stored in the ground segments geometric calibration database. Although not being expected to be required after the finalization of the geometric calibration, any trends in attitude performance will be evaluated by an off-line tool analyzing the Marked GCPs Database contents. Should these trends become significant, i.e. surpass a set threshold, a refined set of on-ground orientation matrices or focal length correction coefficients will be created to remove the biases.

2.2.2 Focal Plane Calibration (Optical Distortion Calibration)

Optical distortion calibration was performed during the initial post launch calibration and will be repeated only on a very infrequent basis, if at all. The camera needs to be re-calibrated only if optical distortion problems are identified.
A sketch of the optical distortion model is given in Figure 3.

For optical distortion calibration, it is not suitable to use the routinely gathered cross and along track angular errors in the Marked GCP Database. Instead, a number of radiometric corrected, but

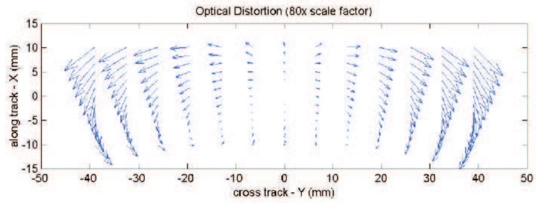

Figure 3: *Illustration of the optical distortion (scaled by a factor of 80).*

geometric raw, image products from several geometric calibration sites are produced. Using an off-line tool, which takes into account the thermal distortion model, the statistics are gathered and saved into a database. Once a sufficient amount of data is available, any trend in the cameras distortion model can be identified and a refined set of pixel projection map polynomials (used to define the location of the CCD array detector positions in the focal plane) can be calculated. The focal plane optical distortion model is described by a polynomial pixel projection map.

2.3 The Radiometric Calibration Approach

The radiometric calibration is divided into two distinct parts:

- the spatial radiometric calibration and
- the temporal radiometric calibration.

The spatial radiometric correction is applied at spacecraft level as well as at ground level during data processing. The temporal correction is only applied at ground level.
All radiometric corrections for the RapidEye data are based on two sets (on-board and on-ground) of gain and offset tables, whose values are used to correct the responsiveness of the relevant detectors. Each detector of each band in each MSI has its own gain value and offset value within the on-board and on-ground tables. All the calibration tables are created and managed by a dedicated sub-system called the Sensor Calibration System (SCS) in the RapidEye Ground Segment.
The on-board gain and offset tables are used to initially optimize the pixel homogeneity (On-Board per Detector Calibration, Section 2.3.2). The on-ground tables are used to adjust the radiances measured by each CCD-element to the previously defined baseline digital number to keep the radiometric response of the detectors stable over the whole constellation and the mission lifetime, to prevent visible striping and banding. This approach results in a reasonably flat fielded and constant response of the whole constellation over time. This means that aside the scaling factor of approximtaly 100 no further adjustments of gains and offsets are necessary to derive radiances from the delivered digital numbers.
In addition, it is possible that single detectors of a CCD line may partly or totally lose their responsiveness during the mission lifetime. Therefore a dedicated Dead Detector Table (DDT) is maintained to keep a record of all non-performing detectors. This DDT will be applied for the spatial corrections on ground while on board the dead detectors are marked appropriately in the on board gain and offset tables.
The On-Board Radiometric Spatial Calibration is applied on every recorded image data set, whereas the On-Ground Spatial Calibration is, on top of the already applied on board correction, applied to all image products except the radiometrically raw sensor level product (L0).

2.3.1 Gathering of Statistical Data used for Calibration

The spatial and the temporal radiometric calibrations will each require their own distinct set of statistical data.
The **spatial radiometric calibration approach** uses statistics gathered from each acquired image dataset. In this context the mean and standard deviation of the responses are calculated representing the statistical data for each detector in each band on each MSI. The statistical data required for the radiometric calibration have to be gathered over sufficiently long periods of time so that all detectors in total will have been statistically exposed to similar radiances. This should result in reasonably uniform mean responses and standard deviations. This large number of statistical data allows the monitoring of changes in the response of each CCD element (detector). Such changes can then be corrected by updating the Gain and Offset Tables.
The **temporal radiometric calibration** uses statistics of data acquired only over selected calibration sites distributed around the world. These calibration sites ideally are characterized by a high degree of homogeneity and, more important, a low degree of temporal variance. Desert and snow or ice covered areas tend to fulfill these characteristics. Similar to the statistical data set for the spatial calibration, the tile mean and tile standard deviation are calculated and stored in the temporal calibration statistics database.

2.3.2 Spatial Calibration

Detectors imaging an area with uniform reflectance are expected to have a reasonably uniform mean response and standard deviation. If this is not the case and one or more detectors deviate significantly from the neighbors, then this will result in striping within the image products after the processing. The key objective of spatial calibration is to maintain a uniform radiometric response across all detectors of a CCD line, by correcting the response of detectors that deviate significantly from the rest. Therefore the spatial calibration is also known as destriping or flat fielding. The spatial calibration process checks the detectors responsiveness on a regular basis by assessing the collected detector statistics described in the previous section. Changes of detector responses result in the update of the respective gain and offset values in the on-board as well as on-ground tables. By applying these updated values the detector response becomes more uniform avoiding any striping and banding within image products.

On-Board per Detector Calibration

The on-board calibration is the first step of the spatial calibration. As previously mentioned, the payload radiometric correction factors (gain and offset) are maintained on the ground, updates being uploaded to the spacecraft and applied using a polynomial approach (eq. 1) to the data onboard.

$$DN_{corr} = (DN_{raw} + offset) \cdot gain \tag{1}$$

The main purpose of this step is to initially optimize the flat fielding of the response. Whilst the homogeneity of the imaged terrain can obviously not be influenced, spatial calibration corrects acquired imagery data of poor homogeneity caused by non-uniform detector response, due to degraded and non-responsive (dead) detectors.

Prior to the download this polynomial approach (eq. 1) is applied using the latest uploaded gain and offset table to correct the raw data values delivered from each CCD element. In case of dead detectors, showing only radiance independent response or no response at all, the mentioned polynomial approach will not achieve the goal of spatially homogeneous L0 data. In this case the specific CCD detector will be marked in the gain and offset table (by setting the gain to a speficially dedicated value and the offset to 0) to indicate the detector as non responsive. Additionally for each dead detector another efficient detector is marked whose value should be used to replace the value recorded by the dead detector. This approach has been chosen to keep the onboard processing effort as low as possible and anyhow achieve as much homogeneity in the imagery as possible. On ground this approach will be further refined lateron (see section 2.3.2). Till now no dead detectors have been identified in the constellation.

On-Ground Dead Detector Calibration

On ground, the initial on board handling of the response for the dead detectors is being refined. The dead detector value is replaced by the mean of its 4 nearest neighbors (see Fig. 4). This processing step is done for all radiometrically processed image products only. Sensor level products will be delivered with the pixel values calculated on-board.

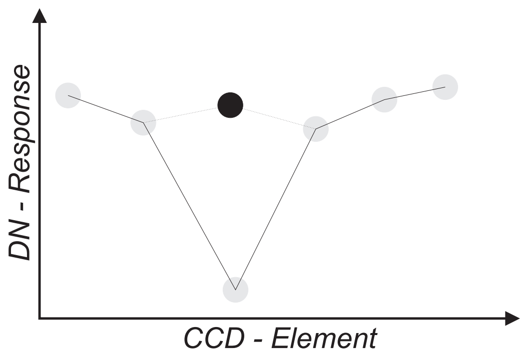

Figure 4: *Schematic sketch of the interpolation of dead detector radiance values. The dark point is interpolated using two neighbors on its left and two on its right side.*

On-Ground spatial Calibration

Also for this calibration step the key objective is to analyze the variations in the performance of each CCD element compared with its neighbors and to prevent striping or banding effects which may be discernible in uniform areas such as lakes, oceans, saltflats or deserts.

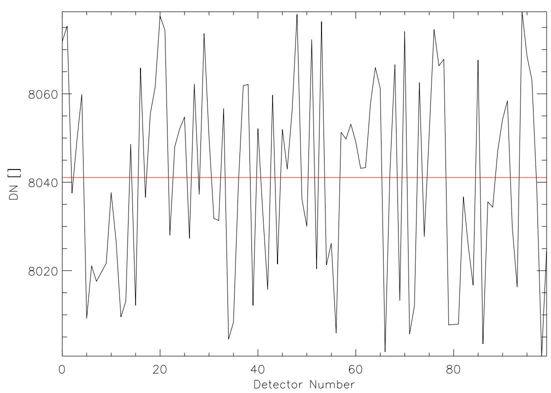

Figure 5: *Schematic sketch of the spatial calibration statistics overlayd by an idealized flat response (red line)*

Figure 5 sketches the mean response of the first 100 detectors of the 12.000 detector line of one spectral band over a time range of several months which leads to a statistical mean over several thousands of image takes with up to 30.000 lines each. This large number is necessary to exclude the variation introduced by scene content. The red line sketches the idealized response. To update the on ground gain and offset tables the statistics are subdivided into several bins of different radiance levels. A DN bin is a range of DN values whose response is linear within the range. A DN bin is bounded by a lower and an upper DN value. These DN bins cover the entire sensor response curve of interest.

Based on the mean DN of an image take, a record is assigned to a DN bin. Within each DN bin, all records are combined together to establish the desired / target response. Based on these bins and the fitted curve updated correction coefficients are produced, one set per detector. This method simultaneously improves the uniformity of the response curve in each DN bin against its own target response (see Fig. 6).

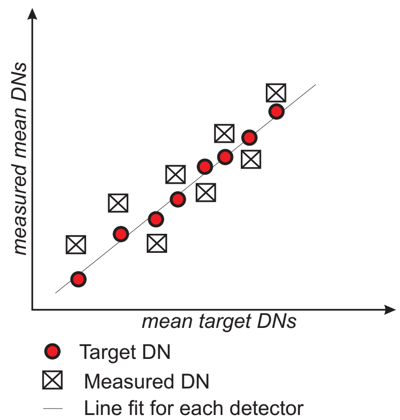

Figure 6: *Schematic sketch of the gain and offset adjustment using bins*

RapidEye decides whilst regularly reviewing the statistics to update the gain and offest tables on demand.

The flat field correction of the image date using the gain and offset tables is done using the polynomial approach given in eq 2.

$$DN_{corr} = (DN_{raw} \cdot gain) + offset \tag{2}$$

2.3.3 Temporal Calibration

Over time sensors change their response behavior because the CCD detectors' sensitivity decreases. The RapidEye temporal calibration approach accounts for this behaviour. The overall goal is that the maximum per band deviation over the whole constallation and over the mission lifetime is better than 5%.

To define a radiometric baseline and to monitor the radiometric behaviour of the spectral bands a set of 32 temporal calibration sites is recorded on a monthly basis. As an optimum these calibration sites cover the whole range of natural brightness levels, are reasonably homogeneous and invariant over time. The sites used for the RapidEye temporal calibration approach are located in Northern Africa, Arabia, Bolivia, Australia and China.

Using the responses of these calibration sites a radiometric baseline is defined using the statistical mean responses for each band over the whole constellation. To define this final baseline with a sufficient statistical confidence approximately one year of operation and test site collection is necessary. This baseline defines the standard RapidEye response. During the mission lifetime the real response is checked against this baseline on a regular basis and if necessary the on-ground gain and offset tables are adjusted in a way that the baseline response is met within tight thresholds.

Currently the deviations of the single bands are as given in table 2 and meet the given requirements well.

Blue Band	2.3135%
Green Band	2.5001%
Red Band	2.6157%
Red-Edge Band	2.6160%
Near IR Band	1.2873%

Table 2: *Maximum spacecraft to spacecraft deviations for each of the five RapidEye bands*

The calibration site statistics gathered to control and update the temporal calibration baseline is always evaluated based on the previous calibration settings. Following this approach it is given with a high level of confidence that the overall response of the constellation is constant over the whole operational mission lifetime. Additionally through to the fact that the first calibration parameters have been created on ground using absolute calibration strategies, assuming that there were no major influences from launch and early orbit maneuvres, absolute calibration is maintained during the operation phase of the detectors. To confirm this assumption and to measure the real deviations from the absolute radiance values RapidEye together with an experienced partner is currently performing an absolute vicarious calibration campaign (see 2.3.4).

2.3.4 Absolute Calibration

The main task of the absolute calibration is to check if changes to the pre-launch laboratory calibration of any of the RapidEye Multi Spectral Imagers have occurred since launch. Absolute calibrated data is necessary for a wide variety of high accuracy thematic applications. Radiometrically corrected RapidEye image data is nominally provided with the absolute calibration parameters applied.

For absolute calibration a vicarious calibration approach is applied. Railroad Valley Playa and Ivanpah Playa (Nevada, USA) are used as calibration sites. From these sites from May to October 2009 a total of nine images have been recorded, for RE3 four collects and RE4 five collects. During these imaging campaigns teams from a project partner have taken ground reference data in the field simultaneously with a satellite passover.

The primary data collected during these campaigns, namely ground target spectral reflectance and atmospheric air column parametric data are used as input to MODTRAN4 to develop an accurate top of the atmosphere (TOA) radiance estimate. This TOA radiance estimate is accurate to 3%. These modeled results can afterwards be compared to the actual satellite measurements.

Figure 7 is an example of the preliminary analysis that shows the comparison between the TOA radiance modeled from ground measured data and the TOA radiance measured from space before the application of absolute calibration parameters. The figure indicates that there is a very good agreement between the absolute radiance from RapidEye images and the ground based reference data with only minimal changes in the sensor responsitivity after launch and that the deviations to date even without the application of new absolute calibration are relatively small.

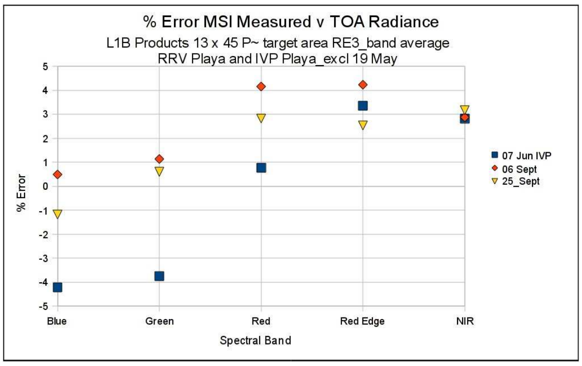

Figure 7: *Comparison between ground measured and spacecraft measured TOA radiance*

Nevertheless to improve the absolute calibration quality further the newly created absolute calibration parameters will be updated and applied to every radiometrically corrected RapidEye image. It is intended to repeat the absolute calibration on a yearly basis as well as to perform a cross-calibration of the five imaging systems in the RapidEye constellation to other operational satellite systems (DMC, LANDSAT, ...).

3 SUMMARY

This article described the calibration concept applied to the RapidEye cameras during commercial operations in order to maintain the accuracy requirements for the RapidEye products and services. Additionally, first results of the currently achieved accuracies have been given.

4 ACKNOWLEDGEMENTS

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