Integrating Advanced Calibration Techniques into Routine Spacecraft Operations

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RapidEye AG is a commercial provider of geo-spatial information products derived from Earth observation image data. The source of this data is the RapidEye constellation of five low-Earth orbiting imaging satellites. The payload is a Multi-Spectral Imager, which does not contain an onboard calibration subsystem. A preliminary in-orbit vicarious calibration campaign was performed after launch to confirm pre-launch calibration results by assessing the spatial response non-uniformity of each sensor. In an effort to improve the relative spatial calibration of the push broom imager and demonstrate the feasibility of an independent spatial calibration methodology, a side slither maneuver approach was developed for the RapidEye constellation. Upgrades made to the RapidEye system to integrate the side slither calibration technique into routine spacecraft operations is presented in this paper along with some in-orbit data to highlight attitude stability results and power generation constraints. This paper also presents sample imagery that contained noticeable spatial artifacts, which were then improved using side slither derived detector correction parameters. A significant improvement in image quality was achieved when compared to our standard correction parameters derived using previous methods.

I. Introduction

Fundamentally to the success of mission operations is the ability to adapt to ever-changing mission needs and enhance the operational system to meet customer requirements. Image data from satellite electro-optical sensors often contains spatial artifacts such as banding and streaking that are caused by detector response variations, factors related to image formation, and the space environment. In order to reduce the negative impact of image artifacts on product quality, the Calibration and Validation Team at RapidEye adopted the Side Slither calibration technique for relative radiometric calibration of the sensor and correction of the imagery. This paper describes the upgrades made to the RapidEye system, in terms of acquisition planning and engineering enhancements, to integrate the side slither imaging campaign into routine spacecraft operations.

RapidEye is a complete end-to-end commercial Earth observation system¹ comprising a constellation of five microsatellites, a dedicated Spacecraft Control Center (SCC), a data downlink ground station service, and a full ground segment designed to plan, acquire, and process millions of square kilometers of imagery every day to generate unique land information products. The major fields of geospatial applications and services are: agriculture, forestry, infrastructure, security, and emergency monitoring. The design and manufacturing of the spacecraft were based upon the SSTL 150 platform developed by Surrey Satellite Technology Ltd. (SSTL). Jena-Optronik GmbH provided the Multi-Spectral Imager (MSI) payload.

The MSI does not contain an on-board calibration subsystem. A preliminary in-orbit vicarious calibration campaign was performed after launch to confirm pre-launch calibration results by assessing the spatial response non-uniformity of each sensor. Over time, detector sensitivity changes require new gain and offset values to correct the banding and striping artifacts in the image data. In an effort to improve the relative spatial calibration of the Push Broom MSI and demonstrate the feasibility of an independent spatial calibration methodology, a side slither maneuver (SSM) was performed with the RapidEye constellation. During SSM, the spacecraft is oriented in a 90° yaw configuration while confining the roll and pitch angle to 0°. The detector array runs parallel to the direction of

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motion. Thus, each pixel on the detector will be excited by the same input level of radiance as they each cover the same tightly confined target areas. Specific target areas over deserts and homogeneous snow covered region allow for effective calibration at differing levels of radiance. While roll maneuvers about the along-track direction are part of the daily imaging activities, imaging activities in non-zero yaw configurations were never foreseen by the manufacturer. This required extensive test campaigns and addition of increased capability within RapidEye's routine operational procedures to meet mission complexity. This paper presents the concept of operations, spacecraft characteristics in $90^\circ$ yaw configuration, in-orbit attitude and power data, and some improvements in RapidEye imagery as a result of this calibration technique.

II. Calibration Concept

Ideally every detector in the focal plane of a remote sensing system would have the same response (mean and standard deviation) when stimulated by the same input light signal. Thus, an image of a uniform radiance input scene would itself be uniform and free from any variations in brightness. However, this is rarely the case and the raw imagery produced by these systems contains visibly discernible and measurable variations called fixed pattern noise. These spatial intensity variations can be attributed to differences in individual detector photo-response, electronic signal processing, throughput variation as a function of the field-of-view of the optical system, and the presence of contaminants within the payload environment. Typically detector responses also change over time during the mission. Relative radiometric calibration of the sensor and correction of the imagery is thus a necessary and on-going activity that is performed to reduce the negative impact of image artifacts on product quality.

A. Preliminary Calibration Approach

Each MSI in the RapidEye constellation must necessarily be viewed as a unique instrument for the purposes of radiometric calibration. A pre-launch calibration of the instruments had produced an initial set of detector gain and offset coefficients. Since the MSI does not contain an on-board calibration subsystem a preliminary in-orbit vicarious calibration campaign was performed after launch to assess the spatial response non-uniformity of each sensor. The previous RapidEye relative spatial radiometric calibration approach is based on the simultaneous derivation of detector gains and offsets’ using the statistics of all scenes collected by the instrument in a given period of time and was developed by the RapidEye mission integrator. Image quality is monitored during the mission life, and the calibration parameters can be adjusted in both a relative and absolute radiometric sense when required to correct for the presence of image artifacts.

After the response function for each detector is determined, subsequent raw images are corrected by applying the derived calibration coefficients to each detector. The correction process assumes that the detector response is linear with respect to input radiance. The previous statistical based operational approach for relative spatial calibration of the RapidEye sensors assumed that each of the detectors in an array on the focal plane of the MSI would eventually be exposed to the same average radiance levels over time. Both the offset and the relative gain for each detector were calculated by fitting a least squares line through the binned detector means from every image collected in a time interval versus the means of the entire array from the same images. Since a majority of scenes lie in the middle of a detector’s response curve, the previous gain and offset calculation provides an adequate correction of medium radiance scenes, but has some issues with very low and high radiance images corresponding to the extremes of the sensor response curve$^2$.5.

The Rapid Eye constellation uses customer orders to drive acquisitions, and due to the system’s ability to revisit a site everyday and capture normally difficult to capture areas, orders often cover coastal areas, regions with significant cloud coverage, and other highly variable content scenes, which would not be feasible for other sensors to capture. A large amount of cloud-filled and land/water transition scenes can cause problems with the gain and offset calculations in shorter time frames when using a statistical based approach.

B. Side Slither Calibration Approach

In an effort to improve the relative spatial calibration (i.e. detector response equalization) of the MSI and demonstrate the feasibility from an operational perspective of an independent spatial calibration methodology, a side-slither campaign was performed using all of the satellites in the RapidEye constellation. Pseudo-invariant and spatially uniform terrestrial scenes that included desert and snow/ice fields were imaged with the sensor in a ninety-degree yaw orbital configuration. In this configuration, each detector on the focal plane was positioned parallel to the ground-track direction thereby imaging the same segment of ground and exposing each detector to the same target radiance. This maneuver produced a radiometrically flat-field input to the sensor so that the relative response of each detector was determined for the same exposure level and compared to the array average.
Figure 1: Side Slither sampling of a ground target and the resulting image.

Ideally when a side-slither image is processed a given point on the ground is seen as a forty-five degree line in the resultant image. This is because, a given point on the ground is sampled by a detector and is then translated over one column and down one row (in the processed image) during each successive integration period as the array moves along the target. The side-slither scanning and the resulting image formation concept are illustrated in Fig. 1.

C. Side Slither Calibration Approach

A number of sites from North Africa were initially considered for acquiring side-slither data including the CEOS radiometric calibration sites in Libya, Algeria, and Egypt as well as the land-sea transition between Libya and the Mediterranean. The first set of side-slither data, acquired by RE5, was along a north-south line passing through Libya. These results were not promising due to scene content variations and pointing instability issues with the spacecraft that were later corrected. In addition to these sites, several regions in the Arabian Peninsula were investigated. These regions are in general uniform with minimal directional variations and were deemed suitable for side-slither imaging.

After inspecting all of the imagery from these regions, the sites over Saudi Arabia showed the most promise, and three target areas within Saudi Arabia were selected. Finally, high reflectance snow/ice regions in Greenland and Antarctica were also chosen. These sites produce radiance values that span the mid-to-high radiance portion of the MSI dynamic range. The Greenland and Antarctica sites are more uniform and excite the sensor at a higher radiance level than the Saudi Arabia sites and are therefore more desirable targets. By choose sites in both Greenland and Antarctica, access is available to these preferable sites for most of the year, but for the few months out the year were neither target is adequately illuminated, Saudi Arabia fills in nicely. When they are available, the large size and high/low latitude of the Greenland and Antarctica sites also allow for more imagining opportunities than Saudi Arabia. Figure 2 shows the locations of the three Saudi Arabia sites, the three Greenland sites, and the Dome C target, using overlays from GoogleEarth Mapping Services.

Figure 2: Desert sites on the Arabian Peninsula, Snowfield sites in Greenland and Dome C.
III. Spacecraft Operations

RapidEye has an end-to-end commercial Earth Observation system comprising a constellation of five spacecraft, a dedicated Spacecraft Control Centre (SCC), a data downlink ground station service, and a full ground segment designed to plan, acquire, and process over 4 million square kilometers of imagery every day to generate unique products. The 5 spacecraft are nominally equally spaced around the orbit, so that they cross the equator at intervals of approximately 19.4 minutes. Important orbit and payload parameters are described in Table 1. The inclination of the orbit is chosen such that the orbit is Sun-synchronous: on each orbit, each spacecraft will cross given latitude at the same time. Thus, two successive ground tracks of one satellite feature approximately 2700 km distance at the equator. Subsequently, the ground tracks of two successive satellites have an equatorial ground separation of approximately 540 km distance.

Table 1: Orbit and payload parameters of RapidEye spacecraft.

<table>
<thead>
<tr>
<th>Orbit Characteristics</th>
<th>Value</th>
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<tbody>
<tr>
<td>Type</td>
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<tr>
<td>Altitude</td>
<td>630 km</td>
</tr>
<tr>
<td>Period</td>
<td>97.2 minutes</td>
</tr>
<tr>
<td>Equator crossing – descending node</td>
<td>11:00:00 AM</td>
</tr>
<tr>
<td>Inclination</td>
<td>97.9 degrees</td>
</tr>
<tr>
<td>Global coverage</td>
<td>Between latitudes 75N and 75S</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Payload</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Type</td>
<td>Multispectral Pushbroom Imager</td>
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<tr>
<td>Spectral Bands</td>
<td>Blue (440-510 nm)</td>
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<tr>
<td></td>
<td>Green (520-590 nm)</td>
</tr>
<tr>
<td></td>
<td>Red (630-685 nm)</td>
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<tr>
<td></td>
<td>Red Edge (690-730 nm)</td>
</tr>
<tr>
<td></td>
<td>Near Infrared (760-850 nm)</td>
</tr>
<tr>
<td>Ground sampling distance</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Swath width</td>
<td>77 km</td>
</tr>
</tbody>
</table>

The objective of the mission is Earth observation with the following characteristics: (1) Global coverage, and (2) Daily revisit. The daily revisit capability is accomplished by across-track roll maneuvers of the satellites. Taking the sensors field of view (7°) into account, two satellites have to be capable of performing a ±20° roll maneuver to cover all areas around the equator. At higher altitudes, both North and South, the ground track separation is reduced, and thus the roll angle required for daily revisit decreases.
An overview of the information flow within the operational framework of RapidEye system is shown in Figure 3. The acquisition planning system (APS) in the ground segment generates command files (Acquisition Schedules and Payload Command Files) that are passed to the SCC. The SCC processes the Acquisition Schedules to produce a Sked file, containing a detailed sequence of telecommands to be executed by the spacecraft for the imaging session. The spacecraft is commanded and housekeeping telemetry is monitored via the low-speed S-Band uplink and downlink. Image data and the associated ancillary files from the spacecraft are downlinked via the high-speed X-Band downlink. Kongsberg Satellite Services (KSAT) in Norway provides this service. At the ground station site in Svalbard, RapidEye has access to a dedicated 7.3m antenna and upon request to an additional 13m antenna.

D. Acquisition Planning

The generation of acquisition schedules for five satellites occurs twice, daily, containing plans for two distinct time periods (as shown in Fig. 4): (1) 13:00 – 24:00 UTC, and (2) 00:00 – 13:00 UTC. The main reason for this split is to generate an optimized acquisition schedule using updated weather forecasts (cloud conditions) for customer orders in the system. While the morning session plans for image acquisitions in North and South America (acquired between 13:00 – 24:00 UTC), the evening planning session takes into account orbits over Australia, Asia, Europe, and Africa (acquired between 0:00 – 13:00 UTC). The finalized plans are then coordinated through the SCC to schedule the satellites, and KSAT to schedule the data reception.

![Figure 4: RapidEye planning cycles.](image)

The location of RapidEye's ground segment permits limited contact with the five satellites in a morning and an evening cluster. Each of the two clusters enables the reception of telemetry and the transmission of telecommands and acquisition schedule to each of the satellites three to four times per cluster, with each contact ranging from 5 to 13 minutes. Scheduling of the KSAT resources is done as part of each planning session. KSAT receives reception schedules of the latest planning as well as the latest two-line elements (TLE) to aid tracking.

In an effort to improve the relative spatial calibration of the push broom MSI and demonstrate the feasibility of an independent spatial calibration methodology, images were acquired by performing a Side Slither (SS) maneuver with all spacecraft in the RapidEye fleet. In order to successfully acquire images in the SS configuration, the following stringent requirements were identified:

1. The spacecraft shall be oriented in 90° yaw while confining the roll and pitch angles to 0°.
2. The attitude control accuracy shall be better than ±0.5° in the yaw axis.
3. The Star Tracker shall be enabled during SS imaging operations providing attitude knowledge better than ±0.02° normal to the Star Tracker boresight and better than ±0.045° around the Star Tracker boresight.

There are two tools available as part of the RapidEye system to plan for these SS image sessions, namely: (1) Acquisition Planning System (APS), and (2) Manual Planning Tool (MPT). The APS is used for nominal imaging operations while MPT is used for setting up schedules of non-routine command sequences.
**Acquisition Planning System**

In nominal operations mode, the APS provides the capability to plan and schedule acquisition of imagery based on submitted Acquisition Requests, while taking into account resource constraints and predicted cloud cover. It maintains a set of scheduled activities, and provides the functions to manage these activities. The Acquisition Schedule Service allows the APS to submit planned acquisition-related activities (Acquisition Schedules) and their corresponding payload commands to the SCC. The Acquisition Schedule Processor (ASP) checks these Acquisition Schedules for any command conflicts and also checks whether the Star Track boresight is blinded by the Moon or Sun. Based on the blinding status, the Star Tracker is either enabled or disabled during the image session. An Acquisition Schedule contains a number of activities that are translated by the ASP into Bus commands. The Bus commands associated with each imaging and downlink session are uploaded to the spacecraft (see Fig. 5) along with their respective PCFs.

**Figure 5: Acquisition planning and scheduling process.**

As mentioned earlier, a side slither image acquisition requires the spacecraft to be in 90° yaw configuration while confining the roll and pitch angles to 0°. One of the main constraints of the APS is that it can only set roll attitude maneuvers for planned image sessions. The capability to input yaw or pitch angle commands via APS was not initially considered during the APS design phase. For global coverage capability the only requirement was the ability to roll the spacecraft up to ±20°.

The main advantage of using the APS is that the image-take for side slither calibration can be planned inline with other customer orders in the system. The APS will also automatically schedule the downlink. In the next subsection, a brief overview of the MPT is provided outlining the advantages and disadvantages in planning image acquisitions for side slither (SS) calibration technique.

**Manual Planning Tool**

The MPT is a MATLAB based tool designed by MDA. MPT provides the capability for the user to perform planning activities to support imaging and downlinking operations as well as payload configuration and diagnostic sessions. The MPT augments the capability of APS by providing more manual options. Using MPT for side slither image acquisition poses several challenges and conflicts. They are described as follows:

- In order to avoid conflicts with image and downlink sessions planned using APS, it is important to clearly identify the orbits required for the side slither campaign for each spacecraft. Due to attitude stability
considerations (detail discussion provided in Section III B), the 90° yaw maneuver is executed one orbit prior to the image acquisition time. The next orbit is required for imaging and the following orbit is required to downlink the image data. This introduces at least 3 orbits of outage (see Fig. 6) from nominal imaging operations in order to acquire side slither data.

- The contact times for X-Band downlink has to be determined using the Satellite Tool Kit (STK). This functionality is automated in the APS. MPT would require the user to run an STK simulation to obtain the downlink time window at Svalbard for each spacecraft.
- For the MPT scenario it is also important to estimate the amount of resource utilization that was required for the side slither campaign and convey this information to the APS operator, who may have to adjust the available resources for the sessions planned in the APS.

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The main advantage of using MPT is that the attitude maneuvers associated with an image or downlink session can be entered manually. In the case of SS image acquisition, if planned using MPT, the 90° yaw configuration during the image session will be a part of the Acquisition Schedule File which the APS can then check for Star Tracker blinding events. The drawback is that, any conflicts or complications can only be identified after ASP generates the Activity Schedules.

Concept of Operations

This section describes the operational procedure adopted to acquire images for the SS calibration campaign. As mentioned earlier, the APS has a limitation that it cannot plan for image acquisitions that require a specific yaw attitude angle. However, the spacecraft commanding capabilities in-built in the SCC architecture enables the user to create a schedule file with the associated attitude commands (roll = pitch = 0° and yaw = 90°). This file (sked) can be uploaded independent of the imaging and downlinking activity schedules. Therefore, the only constraint is that the APS should plan for the SS image acquisition by restricting the attitude mode to nadir pointing (roll = pitch = yaw = 0°) and ensuring that no other attitude telecommands are issued in the Acquisition Schedule for the duration of the SS campaign.

The only drawback of this approach is that the ASP will check for Star Tracker blinding events based on the nadir pointing mode and not the 90° yaw configuration of the spacecraft. In order to overcome this limitation, SSTL developed a Star Tracker Blinding Assessment Tool to aid efficient planning for calibration acquisitions. This is a standalone tool capable of providing time periods that bring the Star Track boresight close to the Sun or Moon for a defined attitude configuration. With the help of this tool, blinding occurrences are first checked for nadir pointing mode. If there is no blinding event detected, then it can be assured that the Star Tracker will be enabled in the ADCS task based on Acquisition Schedules generated using the APS. The next step is to check for blinding events associated with the 90° yaw configuration. If a blinding event is detected, then the campaign has to be postponed.

Using the APS to plan for SS acquisitions ensure that the campaign is integrated along with image sessions that constitute nominal payload operations. The spacecraft resources are thus managed using one interface and the flow of information and commands are consistent throughout the planning session. An example of integrating SS imaging campaign (for Greenland target) into routine imaging operations is provided in Figure 7. Based on this operational scenario of using APS to plan for SS image acquisition, Orbit-1 can contain images (customer data) acquired as part of nominal operations. Comparing this to Fig. 6, in an MPT session, it is required to raise an outage for Orbit-1 in order to avoid any conflicts with commands automatically issued using APS. Once the nominal image is acquired then the Side Slither Maneuver can be commanded using a sked. Since the spacecraft is only rotated about the yaw axis, the X-Band transmitters can still be used to downlink the data acquired in the previous orbit. This can be done

Figure 6: Concept of operation for side slither image acquisition planned using MPT.

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during imaging or prior to imaging (in Orbit-2) depending on the X-Band contact time at Svalbard. The spacecraft can be rotated back to nominal attitude configuration after the image is acquired and nominal imaging operations can be resumed right after.

**Figure 7:** Concept of operations for Greenland side slither acquisition planned using APS.

### E. Spacecraft Characteristics

The RapidEye spacecraft was built by SSTL and was based heavily on a flight proven design. The general structural layout has the spacecraft divided into two separate functional volumes. At the base of the spacecraft is the core bus hardware including the launch vehicle separation system. At the top end of the spacecraft is the payload, which is comprised of the MSI and a payload electronics unit (PEU) as shown in Figure 8. Three body mounted solar panels are located on the $+X$ (velocity direction), $–Z$ (zenith), and $–X$ faces of the spacecraft.

**Figure 8:** Coordinate axes defined based on nominal imaging attitude configuration mode.
Figure 8 shows the RapidEye spacecraft coordinate axes during nominal imaging operations mode:

- X-axis is the Roll axis, and is approximately the orbital velocity vector, which points south during imaging operations. A positive Roll (rotation about the X-axis) will cause the imager to point to the East of normal nadir pointing during nominal imaging operations on the sunlit side of the Earth.
- Z-axis is the Yaw axis, and is approximately the imager boresight. When the spacecraft is in nadir-pointing mode, the Z-axis will be the Nadir vector. A positive rotation about the Yaw axis will rotate the spacecraft clockwise when viewed from above.
- Y-axis completes the right-handed triad, and is the Pitch axis. During nominal imaging, the Y-axis points approximately west. A positive rotation around the Pitch axis will cause the imager to point South of nominal nadir pointing.

A Side Slither (SS) maneuver is characterized by a positive 90° rotation about the Z-axis. Figure 9 shows the RapidEye spacecraft in a SS attitude configuration. In this configuration, the nominal roll axis now becomes the new out-of-plane axis of the spacecraft.

1. Attitude Stability

The attitude control system (ACS) relies on four reaction wheels for three axis control with redundant magnetorquer rods for momentum management. Redundant sun sensors and magnetometers provide the coarse attitude knowledge with a Star Tracker providing the high accuracy attitude information. The Star Tracker is mounted directly to the payload optical bench. Its position and angle are designed to minimize the chances of blinding by the Sun or the Moon.

Figure 10 shows the in-orbit data acquired from RapidEye-4 spacecraft. During the side slither window, it can be clearly observed that the spacecraft maneuvers to 90° yaw attitude while confining the roll and pitch angles to 0°. Roll maneuvers (blue) required for nominal imaging operations can also be seen prior to the side slither window. Based on the coordinate frames defined in Fig. 8, the spacecraft Y-axis is normal to the orbit plane. Therefore, due to spacecraft rotation about the Earth, $\omega_Y$ (body angular rate about Y-axis) will be equal to the orbital frequency of the spacecraft, $\omega_Y = \sqrt{\mu_e/R^3} \approx 0.0617$ deg/sec, where $\mu_e$ (km$^3$/s$^2$) = 398600 is the gravitational parameter of the Earth and $R = 7008$ km is the orbital radius. It can be clearly seen from Fig. 10 that in the nominal attitude configuration, $\omega_Y = \hat{\theta}$ and after the spacecraft is in side slither attitude configuration, $\omega_X = \hat{\theta}$ (since X-axis is the normal to the orbit plane after the 90° yaw maneuver).

The settling time required for the maneuver and the control accuracy in maintaining side slither attitude configuration are shown in Figs. 11 and 12, respectively. During the image acquisition period, the ACS is able to maintain approximately ±0.025° accuracy in the yaw axis.
Figure 10: In-orbit data of attitude angles and body angular rates for RapidEye-4.

Figure 11: In-orbit data of RapidEye-4 showing transition from 0 to 90 degree yaw attitude.
2. **Power Generation**

   Keeping the spacecraft in 90° yaw attitude for long duration is not ideal with regards to power generation and usage of battery. This is clearly evident from the configurations shown in Figs. 8 and 9. The orbit brings each spacecraft over the polar region and down the sunlit side of the Earth, from north to south. Figure 13 shows the power generated per array over one orbit for RapidEye-5 in nominal imaging attitude configuration and in a 90° yaw attitude configuration. In nominal configuration, Array-1 and Array-4 on the +X-Panel generates power as soon as the satellite leaves the eclipse period. With slight variations depending on the season, this panel starts generating power when the satellite descends over the Earth North Pole until the spacecraft is inline with the Equator. In a 90° yaw configuration, this panel is turned away from the sun and does not generate any power.

   Array-3 and Array-6 on the -Z-Panel generates the most power when the satellite is in the middle of the orbit (sun-lit part), approximately 20 minutes before and after passing the Earth equator. Since the orientation of the -Z-Panel does not change after a 90° yaw maneuver the power generation remains the same in this configuration. Array-2 and Array-5 is mounted on the -X-Panel. This panel generates power in a nominal configuration in the last third of the sun-lit part of the orbit. In a 90° yaw configuration, this panel lies parallel to the orbital plane. Therefore, depending on the sun-incidence angle, -X-Panel can only generate 10-20% of the maximum power it can generate in a nominal attitude configuration.

   Figure 14 shows the characteristics of the battery discharge for one orbit, starting at the ascending node, in nominal operations and when the satellite is in a 90° yaw configuration. For this particular case, the spacecraft was taken out of operations an orbit prior the beginning of the yaw maneuver. Therefore, the depth of discharge (DoD) value at the beginning of the orbit is lower than its counterpart in nominal attitude configuration. Comparing the DoD level of the battery for both cases, it can be seen that the battery charge period is lower for the 90° yaw configuration although the power consumption is the same in both attitude configurations. In the presented case (Fig. 14), the sun-lit period of the orbit starts after ~15 minutes and lasts until the 77th minute. In this period, the DoD level during nominal attitude configuration decreases from 10% to 5.5%. When the spacecraft is in 90° yaw configuration the DoD level increases from 6% to 10.5%. This shows that the DoD of the battery in the 90° yaw configuration is 9% higher. Therefore, in terms of power generation and battery discharge cycles, keeping the spacecraft in the side slither attitude configuration for long duration is not ideal for the power subsystem.
Figure 13: Power generated by the solar panels in nominal and yaw attitude configuration.

Figure 14: Comparison of battery depth of discharge.
IV. Image Quality Improvements

Figure 15 shows an image taken over Qatar, the United Arab Emirates, and Saudi Arabia. The dark area in the upper right corner of the left and middle figure is the Persian Gulf. The land portion of the image is a high radiance homogeneous desert target. Banding structure is easily visible in such an image. The left image was corrected with normal statistical gain and offset tables. The statistics were collected over a relatively short period of time, one week. The middle image was corrected with the newly derived tables from the side slither maneuver. The difference between the two is clearly visible. The difficulty in trying to estimate gain and offset tables from statistics is that most of the images collected lie in the middle of the dynamic range of the sensor. So statistically derived tables perform well for most images, but they may not correct striping or banding at low or high radiances as visible in the left image of Figure 15.

![Figure 15: Images taken over Qatar and Saudi Arabia: (1) Without side slither correction (left), (2) After side slither correction (middle), (3) Area where the image was acquired (right).](image)

In order to establish and monitor the on-orbit MSI zero-radiance response, an ongoing imaging campaign acquires dark scenes every quarter of a year with each RapidEye sensor. Dark scene data is analyzed in the context of monitoring spatial and temporal variations and identification of trends in the response of the sensors. This data is acquired during imaging events of 10-12 seconds in length that occur over the Pacific Ocean during ascending node passes at the time of a new-moon. The imaging detector column means in each band as well as other statistical properties are computed during analysis of these dark scene images. These column means provide the on-orbit detector offsets for the side slither calibration method. Using dark data and side slither data (from a high radiance target), the full dynamic range of the sensor can be characterized, and gain and offset tables can be found that perform well for all images.

V. Conclusion

The improvement in quality of the images, as evident from the results presented in this paper, shows that adopting the side slither calibration technique into routine operations was worth the work. All spacecraft in the RapidEye fleet perform the side slither maneuver over one target once every three months. The method has been used successfully to provide an improvement in the relative spatial calibration of remote sensing payloads and was deemed a viable adjunct approach for the RapidEye mission.
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References