RapidEye System Commissioning and On-Orbit Performance

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ABSTRACT

RapidEye is a complete end-to-end commercial earth observation system comprising a constellation of 5 small satellites, each with a 5 band multi-spectral camera providing 6.5 m GSD and an approximate 78 km swath, 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 kilometres of imagery every day to generate unique land information products. The system is owned and operated by RapidEye AG, a commercial company providing global geo-information services and data, located in Brandenburg, Germany. MDA is the mission prime contractor and was responsible for the delivery of the space and ground segments, launch of the constellation, and on-orbit commissioning and camera calibration.

On August 29, 2008, the RapidEye constellation was successfully launched. Spacecraft and ground segment commissioning have taken place, and since 30 January 2009, RapidEye AG has taken control of the constellation to begin full commercial operations. The overall RapidEye system is performing well and is capable of collecting more than 4 M km^2 of high quality multi-spectral imagery every day and can acquire an image of any location on earth every single day. The paper describes the overall system commissioning activities that were undertaken and provides a summary of the actual in-orbit performance of the constellation and the system as a whole.

INTRODUCTION

The RapidEye system is a complete end-to-end commercial Earth observation system comprising a constellation of five spacecraft and ground infrastructure to plan, acquire and process several millions of square kilometers of imagery every day and generate unique land information products. The system is owned and operated by RapidEye AG, a commercial company located in Brandenburg, Germany. The five spacecraft were launched in August 2008 and the system completed commissioning at the end of January 2009. Since the completion of this phase, RapidEye AG has assumed control of the system and has operated it commercially..

MDA is the mission prime contractor and was responsible for the delivery of the space and ground segments, launch of the constellation, and completion of the on-orbit commissioning and camera calibration.

The commissioning and calibration of the constellation that was performed included the following elements:

1. Each of the five spacecraft went through a commissioning campaign to confirm full functionality of all systems (prime and redundant) and to demonstrate that it met the performance requirements.

2. The spacecraft constellation was maneuvered into its final orbital configuration where the 5 spacecraft are equi-spaced around a nominal circular orbit.

3. Geometric calibration was performed on all five satellites. This involved updating the attitude sensor alignment and optical image distortion calibration functions using ground imagery. This improved the image quality and the systematic geo-location accuracy.

4. The radiometric calibration was performed using multiple calibration sites located around the

world. Two types of radiometric calibration were performed,

i) spatial calibration which ensured a sufficiently flat response across the detectors in each band, and

ii) temporal calibration which established a radiometric baseline response for all spacecraft that is maintained over time.

5. System level functional and performance tests were performed using both the space and ground segments together to test all operational elements and to establish the key system performance metrics.

SPACECRAFT COMMISSIONING

After successful launch, each satellite began the Launch and Early Operations (LEOP) phase.

LEOP covered all bus units and subsystems and confirmed that the primary functions of S-Band up/down communications, attitude control, propulsion, and X-Band downlink communications were operational. After launch, the spacecraft were in a free tumble state. They are designed to operate in this state indefinitely. In this mode, the spacecraft have only the S-band receivers and the power system operating so they consume very little power. The SCC was initially provided with orbital elements from the launch agency and later from NORAD allowing the SCC to contact each spacecraft as it passed through the contact window over Brandenburg. After communications had been established, the flight software was uplinked and loaded into the On-Board Computer (OBC). At this point, it was possible to start the check-out of all key systems and activate the attitude control system. This allowed the de-tumbling of the spacecraft and the eventual transitioning of the spacecraft into the nominal nadir pointing 3-axis control mode.

After LEOP, the spacecraft commissioning phase was started. In parallel, the constellation orbit acquisition was started for each spacecraft that eventually put the spacecraft into the desired equi-spaced orientation around a nominal circular orbit.

AOCS

The AOCS performance parameters were checked out on-orbit. During image acquisitions, ADCS data was gathered at various operational roll angles that covered the range of expected roll angles to determine the attitude control accuracy and the attitude knowledge accuracy for both the nominal imaging mode (Star Tracker used in the attitude control loop) and also for what is referred to as the degraded mode (Star Tracker not in the attitude control loop). The latter is the back-up mode should the star tracker data not be available. The "true" position was determined from imagery by using known ground control points on the ground that had a high geolocation knowledge accuracy (in the several meters range).

For the attitude control accuracy in the nominal imaging mode, the measured peak attitude control error was 0.5 deg, 0.2 deg, and 0.3 deg in roll, pitch and yaw respectively. The peak error is the worst case error observed over multiple image sessions on different orbits. The corresponding measured peak attitude knowledge error was 0.04 deg, 0.07 deg and 0.20 deg in roll, pitch and yaw respectively.

In the degraded mode (without the star tracker), the attitude determination is performed by using sun sensors and magnetometers. In this case, the measured peak attitude control error was 3.5 deg, 3.1 deg, and 6.0 deg in roll, pitch and yaw respectively. The measured peak attitude knowledge error was 3.2 deg, 2.7 deg and 6.0 deg in roll, pitch and yaw respectively.

Battery Health Assessment

The 15 A-hr Li-Ion battery used in the spacecraft is one of the key items that drives the mission lifetime. Therefore, a careful checkout was performed to measure the battery temperature, the average peak-to-peak depth of discharge during imaging operations, and the initial battery capacity (at Beginning-of-Life). Data was collected over numerous orbits under different operating scenarios. The measurements confirmed that the battery is operating within the parameters' nominal and has ample margin to meet the 7 year operational lifetime requirement.

End of Life Power Margin

An assessment of the power margins was performed using the measured power consumption of all units on each spacecraft during operations. This included, among other things, determining the orbit average payload heater power consumption and also taking into account the solar array temperatures. To estimate an End-of-Life (EOL) case, the appropriate degradation factors were applied to the solar array power generation and to the solar array temperatures. The EOL orbit average power generation was determined to be 54.1 W, thus confirming that positive power margins will remain available at EOL.

Propellant Margin

The spacecraft uses a cold gas propulsion system with Xenon as the propellant. Each spacecraft carried 12 kg of Xenon propellant at launch. The propellant EOL margin was assessed at the completion of the orbit acquisition phase for the constellation.

At the completion of the orbit acquisition phase (i.e., where all spacecraft are properly phased so that they are equi-spaced around a desired nominal orbit), the amount of remaining propellant varied between 9.15 kg to 11.8 kg (as some spacecraft required more orbit manoeuvring than others to be phased correctly). This is considerably higher than was initially budgeted and is primarily due to the highly accurate orbit injection achieved by the DNEPR launch vehicle.

To determine the expected minimum EOL propellant margin, the propellant budget analysis that was performed prior to launch was updated using the actual propellant mass remaining at the beginning of operations (i.e., 9.15 kg), using the in-orbit measured Isp of the propulsion system (determined to be 47.7 sec), and using the actual orbital properties of the satellites. This showed that at EOL there is >50% propellant margin remaining.

Payload

Each of the RapidEye spacecraft has a multi-spectral imager. The optics system is based on a reflective Three-Mirror-Anastigmat (TMA) design. The focal plane used conventional linear CCD detectors, one for each band.

Basic parameters are:

- Effective Focal Length : 637 mm
- Entrance Pupil Diameter : 147 mm
- f-number: 4.3
- Spectral Bands: Red, Green, Blue, Red-Edge, Near Infra-Red
- Detector: CCD with 12,000 pixels per band

The statistics of the detector response for each CCD were collected. A detector whose response was above or below the mean ± 3σ value would have been considered to be bad. No bad detectors have been found.

Once the payloads had been thermally stabilized (shortly after powering on the payload operational heaters) and all health check activities had been completed, there was a need to confirm the optical performance characteristics and recording capabilities that had been formally verified in the laboratory. The following are some examples of the performance characteristics and recording capabilities that were measured.

- The measured along track viewing angle between the 5 spectral bands is < 0.018 rad.
- The measured band-to-band parallelism is < ±50 pixels.
- The measured nadir ground sampling distance (GSD) in the along track and across track directions is ≤ 6.5 m.
- The payload on-board mass memory unit contains three memory boards of 16 Gbits each. This was demonstrated to allow capturing image strips of up to 1843 km in length (with all bands and lossy compression providing an effective compression ratio of 4.8). The gaps between successive images were shown to be < 50 km.

ORBIT ACQUISITION & CONSTELLATION PHASING

Orbit Injection

The RapidEye constellation was successfully launched on August 29, 2008 aboard a Dnepr LV. Figure 1 shows the injection accuracy achieved for each spacecraft with respect to the initial nominal radius, 7012 km, and phase angle, 97.988 degrees. Note that the origin of the plot in Figure 1 corresponds to the targeted orbit. The spread of the spacecraft semi-major axis relative to the target, which is shown in Figure 1, is exactly as expected since the DNEPR vehicle continues to accelerate while the spacecraft are released one at a time. The achieved injection accuracy was achieved is very good, falling well inside the desired envelope (shown by the blue and red diamond outlines in the Figure 1).

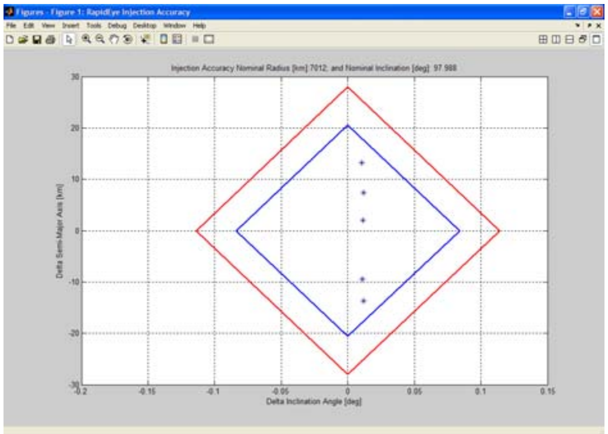


Figure 1: Injection Accuracy

Constellation Phasing

Constellation phasing of the five satellites started during LEOP and continued throughout the System Commissioning and Calibration phase as a background task. This was performed over approximately a four and a half month period to minimize the needed propellant. The phasing of the RapidEye constellation was completed by mid January where the spacecraft were equi-spaced around the desired nominal reference circular orbit.

RapidEye-3 (RE-3) was selected as the reference spacecraft for the phasing operation. Initial spacecraft propulsion system firings for each spacecraft were planned and performed to initiate the slow drift of the orbits to achieve the required constellation phasing relative to the reference RE-3. The constellation phasing parameters of each spacecraft were monitored continuously and propulsion system firings were performed as needed to complete the phasing activity of each spacecraft over the four and a half month period.

The results of phasing phase were as follows:

- All satellites are orbiting at approximately 7007 km and at an inclination of 97.98 deg.
- The semi-major axes of the spacecraft orbits are all within a 15m band.
- Each satellite is nominally equi-spaced around the orbit plane within the range -0.8% to +1.2% of nominal for all spacecraft.

GEOMETRIC CALIBRATION

The geometric calibration involved performing updates to the telescope optical/thermal distortion calibration, effective focal length correction, and also establishing the camera alignment coefficients relative to the spacecraft attitude sensors. A set of Geometric Calibration Tools (GCT) were developed that were part of the ground segment that performed the update to the geometric calibration parameters.

To perform the optical/thermal distortion calibration, the following data was used:

- ortho-rectified product images and their associated acquisition models,
- fine DEMs, and other metadata information from the RapidEye Ground Segment,
- external high-accuracy reference ortho-rectified images

The GCT can generate image residuals from a dense grid of correlation peaks. Using these residuals, MDA analyzed the accuracy of the initial geometric calibration parameters and generated updated parameters.

The Optical/Thermal Distortion Calibration Tool (OTDCT), a component of the RapidEye GCT, is used to refine the focal plane pixel projection map (optical and thermal), as necessary. The OTDCT allowed MDA to selectively choose the parameters to refine.

OTDGC was performed on a given satellite and band combination relative to the red band, and had to take into account the thermal distortion model of the focal plane.

For the RapidEye telescope, the optical distortion was not expected to be affected by telescope temperature, the focal plane however would be affected by focal plane temperature. Therefore, the thermal distortion only addressed the distortion of the focal plane with a change in focal plane temperature (e.g., contraction or expansion).

The Camera Alignment and Scale Calibration (CASC) produced the initial updated camera orientation matrix and effective focal length. This calibration addressed the larger geometric errors of attitude and scale biases and was performed only on the red band of each spacecraft.

As it was not possible to distinguish between errors in spacecraft altitude and errors in focal length – both were treated as a single combined scale error, which would be corrected by adjusting the effective focal length in the ground processing.

The Camera Alignment and Scale Calibration Tool (CACT), a component of the RapidEye GCT, was used to analyze and refine the camera orientation matrix and the effective focal length of the telescope.

The result of performing CASC was an updated orientation matrix and effective focal length for each band on each satellite.

The geometric calibration was performed to improve the overall image quality and to improve the systematic geolocation accuracy.

RADIOMETRIC CALIBRATION

The radiometric calibration that was performed for RapidEye was targeted at maintaining the radiometric response of each satellite to within +/-2.5% of an radiometric baseline that was established during the calibration phase. The idea is to establish a consistent radiometric response across the imaging sensors of all RapidEye satellites over time.

To accomplish this objective, a set of tiles with a reasonable degree of spatial radiometric homogeneity and a low degree of temporal variance were chosen as radiometric calibration sites, so that the imaging sensor response from observing a particular calibration site would be nearly the same for all RapidEye satellites with minimal variation over time. A baseline response was established for each calibration site as the average response of the imaging sensors from all satellites for a given band. After the baseline had been established, the imaging sensor response from each satellite for a given band was periodically compared to the baseline for that band. If it was determined that over time the response of a particular imaging sensor was trending away from its corresponding baseline, then its response was corrected back toward the baseline. By keeping the response of all imaging sensors close to the constellation-wide baseline, we are able to maintain a reasonably consistent relative radiometric response across all RapidEye satellites.

To achieve this objective, MDA validated potential Temporal Radiometric Calibration (TRC) sites and down-selected to the minimum number of stable sites.

Throughout commissioning and calibration, MDA continuously planned and collected images over the radiometric calibration sites and extracted and recorded tile statistics.

The Temporal Radiometric Calibration Tool (TRCT) was then used to generate updated Radiometric Calibration Tables (RTC) used for on-ground image processing. The TRCT adjusts the radiometric calibration parameters to maintain a uniform relative radiometric response across all RapidEye imaging sensors at any given band over time.

Using the TRCT, having down-selected which tiles will be used for calibration purposes, a baseline was generated for each of the 5 bands and stored in the TRCT. This baseline comprises the following information for each tile:

- Tile ID
- Mean Tile Radiance (mean radiance of tile, averaged over all images from all satellites)
- Standard Deviation of Mean Tile Radiance (standard deviation of mean radiance over all images from all satellites)
- Mean Tile Standard Deviation (standard deviation of radiance of tile, averaged over all images from all satellites)
- Standard Deviation of Standard Deviation of Mean Tile Radiance
- Number of images used in determining the baseline
- There are various sources of uncertainty in the TRCT determined corrections.

The radiometric calibration was successfully performed. The relative radiometric accuracy that was achieved across the constellation is +/- 0.5%, which is well within the required relative accuracy of +/-2.5%.

RELATIVE CALIBRATION USING THE MOON

It was also decided to develop and validate a relative radiometric accuracy measurement approach using lunar images acquired during the system commissioning and calibration phase. This was in addition to the temporal radiometric calibration approach, described above, that was used to support validation of the radiometric calibration results.

During each full moon event, starting in December 2008, a series of image sets were collected by the

RapidEye spacecraft. An image set consisted of up to five spectral images of the moon taken from the same orbit location within a period of ~80 minutes – by each spacecraft in succession (see Figure 2).

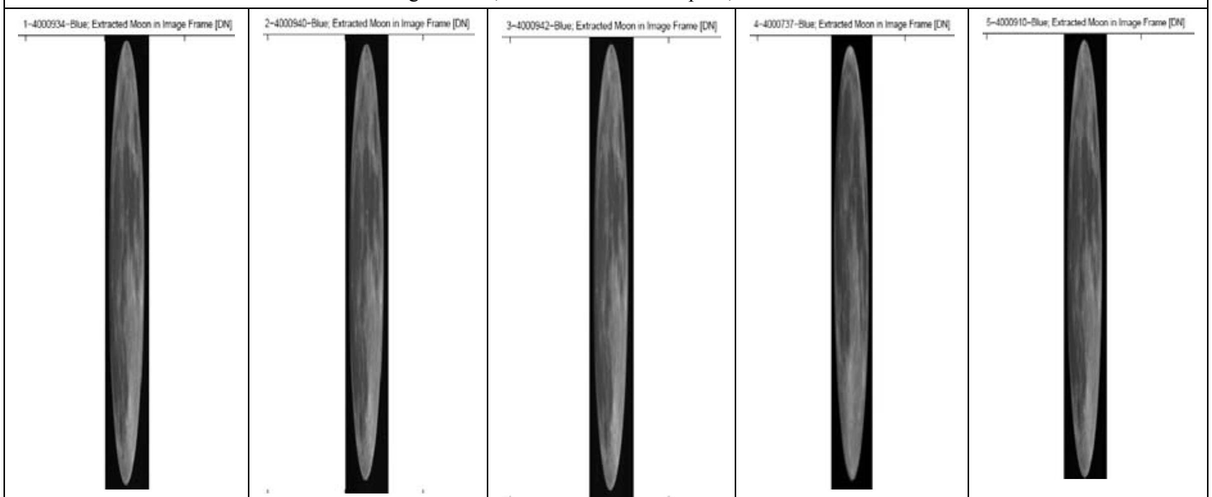
The integrated irradiance over the illuminated lunar disk provides a metric by which to compare the radiometric response from each satellite across the constellation without the variations of the Earth’s atmosphere. These test results corroborated the relative radiometric calibration results.

Other advantages of the lunar images include the ability to perform MTF measurements using an edge response method and temporal radiometric calibration using a data series built-up over time.

The temporal radiometric calibration could potentially also benefit from the spectral irradiance model of the moon obtained from the Robotic Lunar Observatory (ROLO) project. The ROLO project has established a spectral irradiance model of the moon that accounts for variations with lunar phase through the bright half of a month, lunar librations, and the location of an Earth-orbiting spacecraft.

The comparison was performed against the public domain irradiance model and not in conjunction with the ROLO radiometric calibration service managed by NASA-Goddard Space Flight Center. The benefits of extending this work to use the ROLO radiometric calibration service is currently under investigation by MDA and RapidEye AG.

Image Set: 21; Full Moon Event: 9Apr09; Band: Blue



RE-1	RE-2	RE-3	RE-4	RE-5

Figure 2: Example of a Lunar Relative Radiometric Image Set (The extracted moon images are still in Focal Plane Frame and not yet converted to engineering radiance units and re-sampled.)

SYSTEM LEVEL PERFORMANCE TESTS

Modulation Transfer Function (MTF)

One of the drivers of the MTF requirement for the RapidEye system was the need to determine field boundaries in an automated way. To satisfy this business-driven need, the technical requirement for the system specifies a minimum MTF of 10% at Nyquist for both across track and along track for all spectral bands.

The MTF performance of the system is determined primarily by the optical performance of the telescope. MTF tests were performed on the ground with the camera in the laboratory, and also again at spacecraft level both before and after environmental tests. The pre-launch MTF performance is summarized in Table 2. MTF tests were then performed on-orbit during the spacecraft commissioning period. The objective of the on-orbit tests was to confirm that the MTF performance was not significantly degraded as a result of the launch and with the actual on-orbit camera thermal environment.

There are two primary effects that were of particular concern with the Three Mirror Anastigmat (TMA) design of the telescope. The first one was that the mechanical loads during launch could have caused small movements in the mirror mountings and thus created a de-focus effect that would degrade the optical performance of the telescope. The second concern was the thermal gradient between the front and the back of the telescope. If the thermal gradient would be too large, then it could, again, result in a de-focus effect and thus degradation of the optical performance of the telescope. To minimize this thermal gradient effect, the telescope was equipped with a thermal shroud and heaters. Thermal modeling and tests were performed on the ground, allowing a characterization of the expected gradient.

The approach used to measure the MTF on-orbit was to image several test sites featuring sharp boundaries. Most of the images used land-water boundaries. Several test sites were used to perform these tests. Figure 3 depicts a typical MTF assessment based on actual imagery.

Table 1 lists the on-orbit MTF performance per band, averaged over the 5 spacecraft. This is compared with the pre-launch measured values.

The differences between the pre-launch test results and the on-orbit test results are principally caused by quality of the MTF calibration sites (which used natural features as opposed to specific MTF targets intended for ground calibration) and the variation in the atmospheric conditions. Hence, it was expected that the MTF results would be on average worse than those measured in the lab. However, the results show that even with the conservative nature of the measurement approach, the MTF results were still well above the requirement of 10%. This shows that the telescope thermal design and temperature control is working as expected and that the telescope did not suffer any misalignments or other degradations during launch.

Table 1: MTF Performance of the RapidEye Spacecraft

	On-orbit test results Averaged over 5 spacecraft		Pre-launch test results Averaged over 5 spacecraft	
Band	Along track MTF	Across track MTF	Along track MTF	Across track MTF
Blue	18.3	19.9	19.7	26.8
Green	15.1	18.6	21.5	28.5
Red	19.6	17.0	18.8	22.1
Red edge	21.2	16.7	18.6	20.1
NIR	14.4	13.1	17.1	15.9
Requirement	**10.0**	**10.0**	**10.0**	**10.0**

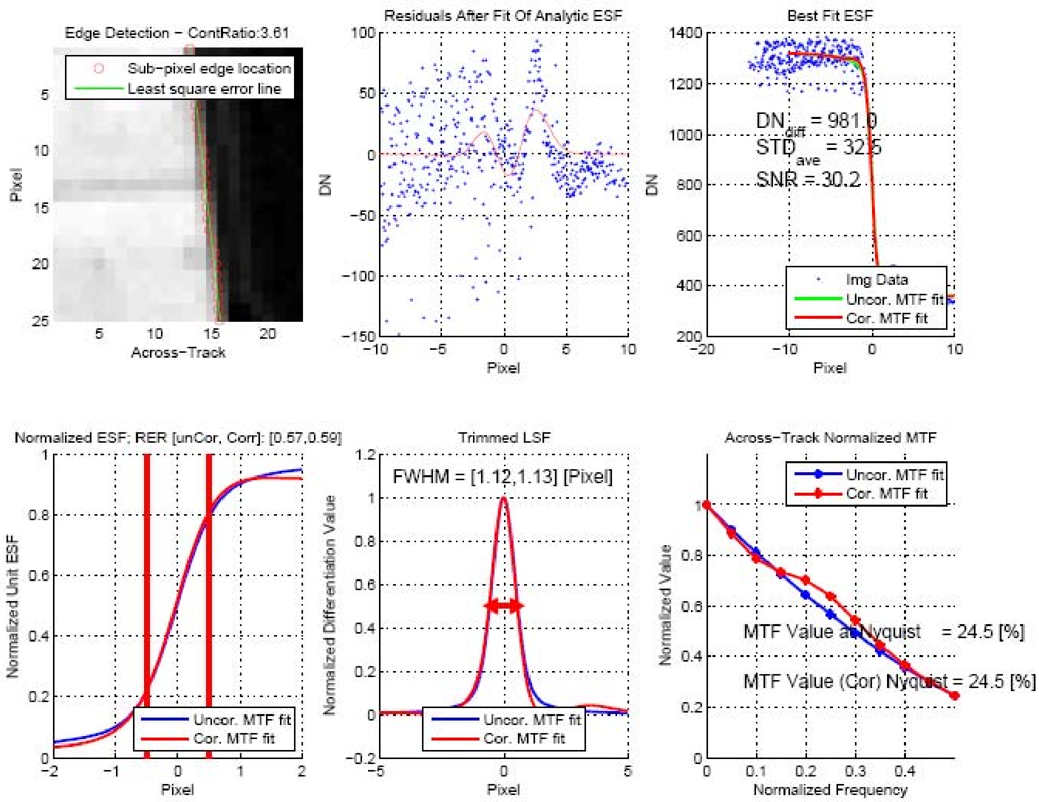


Figure 3: MTF Example

Capture Capacity

The system is required to be capable of capturing 4 million km² of imagery of the accessible area per day, using real-time data downlink and transfer. A capturing capacity test demonstrated the system was capable of capturing 4.75 million km² of data over a 24 hour period, neglecting cloud cover and with the compression settings selected to obtain an average of approximately 2.5bpp. Note that this result applies for the particular test case that was conducted and not necessarily true for all operational cases. The result does however imply that for the general case, the system can capture >4 M km² of imagery per day.

Processing Capacity

The system is required to be capable of processing up to 2.1 M km² of raw imagery per day into Level 2Go ortho-products, a day in this case meaning 16 hours. A processing capacity test demonstrated that the system was able to process 2.43 million km².

In addition, there was a requirement for the system to be capable of cataloguing 4.0 million km². This test was performed by using 4.2 million km² of pre-downlinked data that was ingested into the GS at a quantity and frequency similar to that of a real-time downlink and transfer from the X-band station.

Digital Elevation Maps

The RapidEye constellation is capable of producing Digital Elevation Maps (DEMs) and therefore had a number of requirements related to throughput and accuracy of DEMs.

The system is required to generate 50,000 km² of observed height DEMs per day based on the following assumptions including:

- Number of Work Positions: 3
- Number of Operators: 3
- Operator Work Shifts: 2 shifts per day, 5 days per week

The DEM throughput test achieved 180,000 km^2, with some manual editing, in less than the allotted time.

With respect to DEM accuracy, assuming a terrain flatness of <= 10 degree slope and GCPs with an error of <2m (1-sigma), the system needs to be capable of outputting DEMs with the following characteristics:

- absolute vertical accuracy of 19.1m RMSE
- absolute horizontal accuracy 12m RMSE

The DEM accuracy test achieved a DEM absolute vertical accuracy of 9.43m RMSE and a DEM absolute horizontal accuracy of 7.7m RMSE

Band-to-Band Registration and Absolute Geolocation Accuracy

Two important data quality metrics associated of the processed ortho-rectified image products are the band-to-band registration within an image, and the absolute geolocation accuracy of the image product. The registration accuracy of the five spectral bands relative to each other is required to be better than or equal to 0.2 (1-sigma) of a pixel. The requirement for the absolute geolocation accuracy of the ortho-rectified imagery is 11m (1-sigma) or better. This assumes that image data are processed using Ground Control Points (GCPs).

The first step towards assessing if these two requirements were met was to remove all systematic model biases due to alignment errors between the attitude sensors and the camera, errors in scale, and geometric distortions such as smile and smirk. These errors were removed by performing the geometric calibration campaign that involved defining and updating the alignment matrices between the camera bore-sight and the attitude sensors and the geometric distortion parameters. This was described earlier in the paper.

Once this geometric calibration was completed, several images were collected of well known areas, at various spacecraft roll angles. The absolute geolocation accuracy and band-to-band registration were determined by analyzing these images in detail. Table 2 lists the resulting performance of the RapidEye system. This assessment used images that were processed with GCPs that had an accuracy of 7 m (1-sigma). The results in Table 2 show that the performance of the system exceeds the requirements. It should also be noted that no significant effect due to the roll angle was observed, for either the band-to-band registration or the absolute geolocation accuracy.

Table 2: Absolute geometric accuracy and band-to-band registration performance

	Absolute Geometric Accuracy (m)		Band-to-band Registration (pixel)	
	Along track	Across track	Along track	Across track
Mean	5.11	4.38	0.11	0.10
Max	7.39	6.83	0.15	0.10
Requirement	**11.0**	**11.0**	**0.20**	**0.20**

SUMMARY

The Commissioning and Calibration phase of the RapidEye satellite system has now been successfully completed. The paper provided a high level description of the commissioning and calibration campaign that was undertaken, and provided some of the key spacecraft and system performance results. The RapidEye system is now in full commercial operations.