

High Performance Optical Imaging Payloads for Smallsat Missions

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ABSTRACT

This paper describes what we believe is a disruptive technology solution for smallsat optical imaging missions, that combines a new line of cameras that provide very high quality, high resolution imaging, with a low power Payload Controller, Processor and Memory Unit (PCPMU) that provides multi-terabit on-board data storage and high speed data output at a uniquely low price point. Working together with the Rutherford Appleton Laboratory in the UK, MDA is developing the RALCam family of high resolution multispectral cameras, capable of up to 0.5 m GSD imaging from a 500 km altitude. Two related camera systems in the product family are described, one that provides 1.0 m GSD and the other that provides 0.5 m GSD. Key performance specifications for both cameras are given. Hardware testing results are also summarized. MDA are incorporating these cameras and payload electronics into a highly price competitive mission level solution that includes a spacecraft designed and optimized specifically for the RALCam high resolution cameras and a full ground segment that includes the satellite control & tasking, uplink and downlinks, and image processing and archiving which produces very high quality image & information products. MDA's optical spacecraft design that incorporates the RALCam high resolution cameras is also described and key performance parameters are given. Finally, concluding remarks are provided that summarize the key technology and price point enablers. The first system could be launched as early as 2010 and we expect this will change the economics of operational class high resolution optical remote sensing.

INTRODUCTION

The High-Resolution RALCam camera development initiative at MDA is developing two related camera products, a 1-m GSD class camera (RALCam-4) and a 0.5 m GSD class camera (RALCam-5) that provide exceptional image quality but at significantly lower price points than currently available camera systems that offer similar data quality. This development activity is well underway and has involved significant design activity and engineering model testing to confirm the feasibility of the design and in particular the key "price point enablers".

The overall optical payload consists of two main elements,

- 1) the optical camera which includes the telescope and an integrated Focal Plane and Electronics Assembly (FPEA), and
- 2) the Payload Controller, Processor and Memory Unit (PCPMU) which performs all the camera control, data storage, and data formatting.

To help achieve the low price point, the two Hi-Res camera products have been designed to use much of the same hardware and technology. For example, the

FPEA and PCPMU are designed for the more demanding RALCam-5 and use a modular approach that allows configuring the units to also be used for RALCam-4.

The optical camera is being developed by Orbital Optics Limited, a subsidiary of MDA, located in the UK. OOL and MDA have an exclusive partnership for the development of space camera products with the Space Science and Technology Department located at the Rutherford Appleton Laboratory (RAL) site of the Science and Technology Facilities Council. RAL has an enormous amount of experience in space missions, having been involved in ground station operations, and science instrument and spacecraft development programs for more than 45 years. RAL has developed over 150 space instruments and cameras for customers all over the world including the UK Ministry of Defence, ESA, NASA, and major European and U.S. primes.

The PCPMU is an MDA product that is currently under development to be the core payload electronics unit for all of MDA's upcoming space missions (e.g., radar, optical and communications). This development is leveraging MDA's extensive heritage and experience with high speed, low noise digital electronics (e.g., Radarsat-2 electronics, communications spacecraft payloads, LIDAR payloads) as well as the high capacity and low power data storage technology being developed for the Cascade data service (a business MDA is establishing). This is also targeted at achieving world class performance in terms of high speed data rates and data storage capabilities (e.g., scalable to several Tbits of memory) while maintaining a highly competitive price point.

This paper will describe the optical payload technology, provide the key performance parameters, and outline the status of the development program. In addition, a brief description is also provided of MDA's 1.0 m GSD optical spacecraft that is specifically designed for the RALCam-4 camera.

OPTICAL CAMERA

Optical Design

The telescope optical design is a 'Korsch' Three Mirror Anastigmat (TMA) type with two extra fold mirrors which enable the optical path to be fitted in to a very compact envelope. The mirrors are made from Zerodur, a low expansion glass, and they have up to 70% light-weighting applied to reduce their mass. The mirrors are coated with protective Aluminum to give high reflectivity in the visible wavelengths.

The telescope is used in push-broom mode with separate linear detectors and a band-pass defining filter for each channel. The SNR is controlled by TDI (Time Delay Integration) CCDs which allows the entrance pupil diameter to be only used to maintain the optical MTF. Because the telescope contains no lenses, there is no chromatic aberration and hence the focusing is the same in all bands.

The design was optimized to give a near diffraction limited performance over the whole field of view. The front section of the telescope has two on-axis conic mirrors (M1 and M2) giving an intermediate image close to M1. The final image plane is formed by M3 after folding by the two auxiliary flats. There is an accessible exit pupil between M3 and Flat #2 which, coupled with the intermediate image, gives this design excellent stray light control properties.

The optical layout is shown in Figure 1 below.

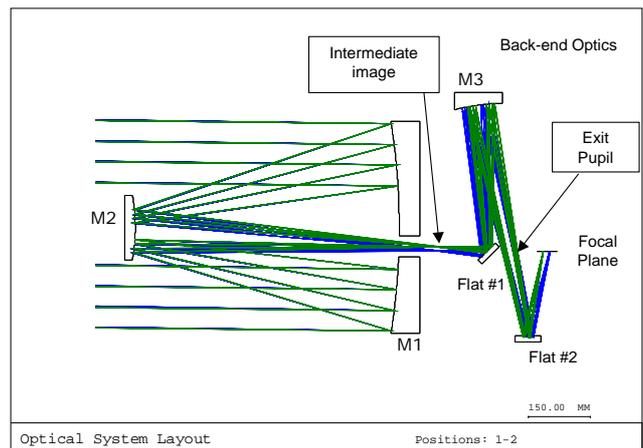


Figure 1: Optical System Layout

For RALCam-4, the telescope focal length is 6000 mm, the entrance pupil diameter is 480mm and the field-of-view is $\pm 0.95^\circ$. RALCam-5 uses exactly the same optical design but is scaled up to have a focal length of 10,000 mm, and an entrance pupil diameter of 800mm.

The TMA design used on RALCam-4 and 5 has excellent stray light control capabilities given by the intermediate image and the accessible exit pupil.

Active On-Orbit Optics (AO³) System

A critical design aspect of this telescope (and any telescope of this performance class) is the positional instability of the optical components relative to M1 that could result from either the launch loads or material changes once in space (such as water absorption of the CFRP material on the ground which can cause small

dimensional changes once in space when the water is outgassed). Maintaining high positional stability of the optical elements has traditionally been a major cost driver and is one of the major impediments to attaining high image quality on orbit. To address this issue for RALCam-4 and 5 cameras, and enable the very high image quality but at significantly lower costs, we are using an approach that is based on the “Active Optics” techniques that have been developed by the astronomy community to achieve ever increasing performance from ground based telescopes.

The basic approach is that rather than relying on maintaining extremely high stability when subjected to the very large launch loads and once exposed to the vacuum of space, we instead use the AO³ system to re-align the telescope following launch. The optics design has been carefully selected & optimized to allow for a simple realignment scheme to maintain high reliability and low cost. The specific techniques used to achieve this alignment are proprietary. It has been shown that the technique is very robust as even in the presence of very large telescope misalignments, which would significantly degrade the MTF, the AO³ system can re-align and focus the telescope to recover to very near pre-launch performance.

Telescope Structure

The primary structure of the camera is made from Carbon Fibre Reinforced Polymer (CFRP). This has the advantage of high stiffness combined with low mass, and through careful design of the laminate, can be tailored to give virtually zero coefficient of thermal expansion. A “camera support frame” attaches to the telescope using a single rigid titanium mount and 3 titanium flexure mounts as shown in Figure 2. This simplifies the interface of the camera to the spacecraft bus. The camera support frame mounts to the spacecraft via three vibration isolators that help reduce high frequency vibration generated by the spacecraft subsystems from reaching the mirrors and causing optical bore sight movement (jitter).

The design for the primary structure (optical bench) draws on the heritage from the RALCam-1 camera which was flown on the UK Topsat mission (launched in 2005), which used the same CFRP material with Aluminum honeycomb sandwich panels to achieve a lightweight and dimensionally stable configuration.

The main elements of the RALCam-4 & 5 structure are the M1/M3 bulkhead panel and the metering tube supporting the M2 mirror assembly (including adjustment mechanism). The bulkhead is a honeycomb panel with CFRP faceskins and an Aluminum core. The tube is made from several CFRP uni-directional layers

(pre-preg) to form a laminate. The laminate is made from high modulus PAN fibres (M55J) and a cyanate ester resin system, which is less susceptible to moisture expansion than epoxy systems and hence minimizes dimensional changes due to moisture absorption.

The M1 mirror mounts on one side of the bulkhead and M3 mounts on the other side so excellent dimensional stability is maintained between these two critical optical components at all times. The two fold mirrors and the Focal Plane Assembly are also attached to the bulkhead panel via a rigid CFRP/Aluminum Honeycomb box structure. This means that four of the five mirrors that make up the optical train are located off a single, stable, structural element. This design feature allows for tight positional tolerance of the optical elements to be maintained following exposure to ground testing and the launch loads.

The M2 support structure consists of three flat like plates arranged at 120 degree intervals around the end of the tube. The M2 mirror and Invar mounting ring are mounted in a CFRP ‘cup’ which in turn is supported by the three plates (collectively the three plates are commonly referred to as a Spider).

The M1 mirror is mounted to the bulkhead panel via three Invar flexures adhesively bonded to the mirror’s perimeter. The advantage of bonding the mounts to the mirror is that minimal strain is induced in the mirror surface so no degradation of the optical performance occurs.

Focal Plane and Electronics Assembly (FPEA)

The FPEA uses two custom CCD detector designs, one for panchromatic and one for multi-spectral use.

The Pan device has 10µm square pixels and is organized to operate as a TDI device with 4196 columns and 96 TDI lines. A facility is included which allows the active TDI length to be altered remotely to allow fine tuning of system sensitivity, using structures derivative from those previously implemented on other space TDI devices. Each device has 4 output amplifiers in order to output data at the required rate.

For the multi-spectral application, the chip design includes 4 separate TDI devices, spaced 1.5 mm apart on the same piece of silicon. Each TDI device is covered with an optical filter. In this case, the pixel size is 40µm square, with 1049 columns and 16 lines of TDI. The data rate from each of these devices is low enough to be taken from a single output for each.

The focal plane layout for RALCam-5 includes a row of 8 packaged PAN CCD chips in a staggered

configuration with 100 pixel overlap and a similar parallel array of 8 MS devices with 25 pixel overlap. For RALCam-4, only 5 Pan and MS devices are used.

The Front-End Electronics (FEE) is packaged together with the focal plane in the FPEA, but is thermally decoupled. Note that the FPEA is designed for both RALCam-4 and RALCam-5. Hence, it is designed to have 8 Pan and 8 MS CCD devices and operates at a 15 MHz clock rate (needed for the 0.5 m GSD). For RALCam-4, only 5 Pan and MS devices are populated, and the unit clock speed is set to operate at 7.5 MHz.

Video processing ASICs are used that provide pre-amplification, Correlated Double Sampling (CDS) and analogue-to-digital conversion (ADC) of the CCD video output signals. The ASICs also provide programmable video gain and programmable video offset control. The CCD video data is digitised to 12 bit precision, and fed from the ASICs as 12 bit parallel data. The data from a pair of panchromatic CCDs and a pair of spectral CCDs are multiplexed into one of four FPGAs. All the digital timing signals needed to clock the CCD arrays and operate the video processing ASICs are provided by a Waveform Generator and Sequencer (WGS) inside the primary FPGA. EDAC is used to enhance the immunity of the WGS RAM to single-event upsets. The error check codes are designed for single error correction and double error detection, and are created/tested by this block each time data is written/accessed.

Each CCD output amplifier is independently driven and decoupled to ensure that there is no crosstalk between the outputs from supply modulation. The CCD bias voltages can be programmed under software control to ease the setup optimization. The housekeeping telemetry circuitry enables monitoring of the FEE's secondary power supply rails, the CCD's DC bias voltages, the FPA's operating temperature, and the FEE's internal operating temperature. A CAN bus controller is used to interface to the PCPMU to accept commands to send the telemetry data.

For the RALCam-5 application, four FPGAs are used to transmit the digitized video data out of the FEE over a number of high-speed serial data links, whereas only 3 FPGA's are needed for RALCam-4. There is also another set of redundant high speed I/O links that interface to redundant boards in the PCPMU. In the event of a failure, the FPGA's can be re-configured based on commands from the ground station to use the redundant set of I/O interfaces.

Thermal

Thermal control of the camera is achieved by a combination of electrical heaters and a passive radiator that mounts directly to the camera. The radiator is located directly above the FPEA and has a high conductivity thermal strap to the Focal Plane Electronics Assembly. During imaging, this FPEA subsystem requires cooling to maintain the CCD temperatures in a suitable range to achieve low noise performance. During non-imaging periods heaters on the radiator are switched on to prevent the CCD from becoming too cold. The camera is conductively and radiatively decoupled from the spacecraft by the Titanium feet & elastomeric camera isolators and multi-layer insulation (MLI) wrapped around the entire body of the camera. Heaters directly attached to the CFRP structure are used to maintain the optimum camera temperature of 20 deg C. Solar input during the daylight part of the orbit will also help keep the camera warm.

Camera Configuration

The RALCam-4 optical camera is shown below in Figure 2.

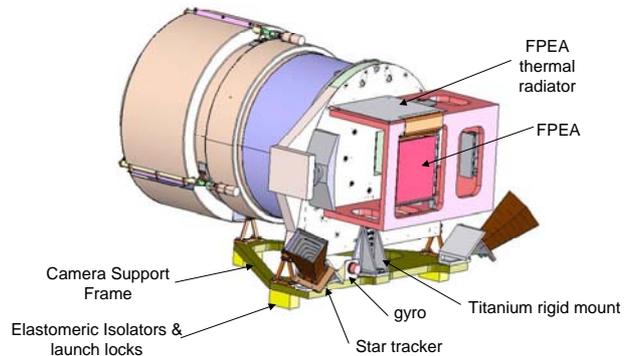


Figure 2: RALCam-4 1.0 m GSD Optical Camera

The integral “camera support frame”, shown in Figure 2, is also used to accommodate the star trackers and gyros used for the spacecraft attitude control and image processing. The camera support frame is also made of the same near-zero CTE CFRP material as used for the telescope structure. This allows for highly accurate geometric calibration of the sensing axes of the star trackers and gyros relative to the optical bore sight during on-orbit commissioning. This significantly improves the systematic geometric accuracy of the system.

The mechanical interface between the camera and the bus is through a set of elastomeric isolators that provide high frequency jitter attenuation. This minimizes the MTF degradation that can result from the jitter caused by reaction wheels and other moving parts in the

spacecraft. For launch, a set of launch locks are integrated into the isolator system to provide the necessary stiffness during launch.

The RALCam-5 configuration is the same as the RALCam-4 shown in Figure 2 although scaled up to have an aperture of 800 mm (as oppose to 480 mm for RALCam-4). It also uses a camera support frame with the elastomeric isolators. However in this case, due to the larger camera size and to allow for a more compact spacecraft design, the camera support frame has two folds so that it tends to wrap around the telescope tube, as oppose to being flat as it is for RALCam-4.

HARDWARE TESTING

A Structural Engineering Model (SEM) of the RALCam-4 telescope has been built that includes the primary optical elements (used dummy optics) and optical bench, metering tube and mirror mounts, and flexure telescope mounts. The SEM is shown below in Figure 3.



Figure 3: RALCam-4 Structural Engineering Model in the Thermal-Vacuum Chamber

The SEM underwent vibration and thermal-vacuum testing to qualification levels. Following the environmental tests, the stability of the primary optics was measured using laser interferometry with optical surfaces attached onto the dummy optical elements. The following summarizes the key results from the test program:

1. The design passed all testing and confirmed the telescope can survive the typical launch environments.
2. Have confirmed the natural frequency of the telescope meets requirements.

3. Have demonstrated that the stability of alignment of the optical elements during the vibration test campaign is well within the alignment correction capability using the AO³ system (with ample margin).
4. The CTE of the telescope tube was measured and found to be $0.2 \times 10^{-6} / ^\circ\text{C}$. This confirmed that the CTE is indeed near-zero, making dimensional changes due to temperature variations negligible.
5. The primary mirror mounting technique to the bulkhead panel was implemented on dummy optics. This was successfully qualified.

PCPMU

The PCPMU is designed as a general purpose, modular unit that can be used in a wide variety of missions. It is intended as a payload controller, processor and memory unit for optical, radar and high bandwidth store and forward communication satellites. The design draws on the heritage from several different programs within MDA that allows for providing very high performance in terms of high speed electronics, high memory capacity (can accommodated up to several Tbits of memory), and low power, but allowing for highly competitive price points compared with other electronics systems of this class. The programs that formed the basis for this design are the Radarsat-2 payload electronics, and the Cassiope 1 Tbit Data Storage Unit (DSU) that uses flash memory devices (Cassiope is a joint science mission for the Canadian Space Agency and a technology demonstration mission for MDA's Cascade high bandwidth store & forward data delivery service, scheduled to launch in 2009).

Another important factor that is a significant contributor to the performance and low price points is MDA's extensive knowledge and expertise in the appropriate use of commercial parts for space. MDA has for many years now been working closely with NASA and major space mission prime contractors on qualifying commercial parts for numerous programs, have been working directly with vendors to support space qualification of their devices, and have undertaken operational programs (such as RapidEye) that have a high percentage of commercial parts that have been qualified for long lifetime applications (7 years).

For the optical payloads, the PCPMU provides the following main functions:

- Instrument Controller: direct interface to the optical cameras to set various operating parameters and control the image timing, interface to the bus and

interprets the high level commands to execute the various operational modes.

- **Optical Instrument Data Interface:** accepts high speed image digital data from the optical cameras that can operate up to 10 Gbps (total input data rate)
- **Image Compression:** the high speed optical image data can be compressed in real time using JPEG2000, with variable compression level settings.
- **On-board Memory:** has on-board data storage in non-volatile memory devices that can be configured from 0.5 Terabit to 4 Terabits.
- **Data Formatting and Output Interface:** Image data is formatted for CCSDS and encrypted and provided in I/Q & clock format to two downlink transmitters simultaneously at data rates of up to 400 Mbps per transmitter.
- **Mechanism Drive Electronics:** used to drive the X-band data downlink antenna gimbals as well as the AO³ mechanisms on the camera (for optical alignment).
- **Power Control:** has an internal power controller, taking unregulated 28V from the spacecraft platform, providing various secondary voltages and switches for the internal modules and the instruments.

The PCPMU can accommodate a large number of standard 6U (eurocard) cards and is designed to be expandable to what each specific mission requires. The cards are wedge locked into a chassis for easy assembly. The configuration can be assembled quickly and avoids space consuming cables. As an example, a typical unit for the RALCam-4 camera would consist of 14 cards, each in a 6U form factor, enclosed in an aluminum chassis. The PCPMU is internally redundant with at least 2 of each card type to ensure single fault tolerance for all functions. For the cards that are redundant, the approach used is cold standby, therefore, only a subset of the total number of boards are powered. Redundancy control is implemented by applying power to the required boards.

The PCPMU housing is machined from a solid block of aluminum alloy. It houses the Printed Circuit Boards (PCBs), the backplane, and all associated brackets. A front and back cover close off the assembly. The PCBs slide into the housing to mate into the backplane. They are then held in place using card-lock retainers. The

backplane distributes and isolates the power and signal lines. The PCPMU configuration is shown in Figure 4.

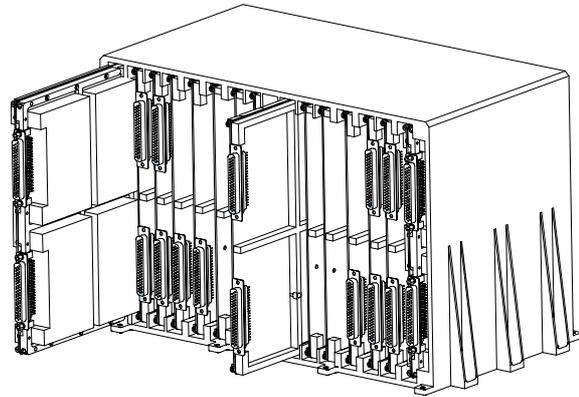


Figure 4: PCPMU Assembly (cover removed)

CAMERA PERFORMANCE SPECIFICATIONS

Table 1: RALCam-4 Performance Specifications

Parameter	Value	Comments
Mass		
Camera	72.7 kg	Includes margin
PCMU	20.9 kg	Includes margin
Power		
Camera - FPEA	60 W	Typical duty cycle is 10%
PCMU - imaging	58 W	Typical duty cycle is 10%
PCMU - imaging & downlinking	82 W	Typical duty cycle is 10%
PCMU - downlink	64 W	Typical duty cycle is 10%
PCMU - data retention	0 W	non-volatile memory
Camera Envelope		
Length	1.17 m	Does not include MLI
Height	0.75 m	Does not include MLI
Width	0.83 m	Does not include MLI
Camera Parameters & Performance		
Pan CCD pixel size	10µm x 10µm	
Number of Pan pixels across track	20,580	Based on 5 CCD devices with 4196

Parameter	Value	Comments
		pixels per device and 100 pixel overlap
Number of Pan TDI stages	96	Selectable
MS CCD pixel size	40 μ m x 40 μ m	
Number MS pixels across track (per band)	5145	Based on 5 CCD devices with 1049 pixels per device and 25 pixel overlap
Number of MS band TDI stages	16	Selectable
Spectral Bands	450-700 nm 450-520 nm 520-600 nm 630-690 nm 760-900 nm	Bandwidths used for SNR calculation The MS spectral band widths can be tailored.
Focal length	6000 mm	
Aperture	480 mm	
Radiometric Resolution	12 bits	
GSD Pan MS	1.0 m 4.0 m	At 600 km altitude and at nadir
Swath Width	20.58 km	At 600 km altitude and at nadir
Pan MTF across track	>16.1%	System level MTF - includes spacecraft velocity, bore sight jitter, thermal effects
Pan MTF along track	>10.8%	System level MTF - includes spacecraft velocity, bore sight jitter, thermal effects
Pan Signal to Noise Ratio (SNR)	146	Pessimistic case. Sun angle = 67.3 deg, TDI level =24,scene reflectance = 0.5, Solar irradiance = 1500 Wm ⁻² μ m ⁻¹
PCMU Parameters & Performance		
Data storage	1.0 Tbit	At EOL (1.5 Tbit at BOL). This is typical. Can be expanded to up to 4 Tbits.
Data output data rate to data downlink Tx's	420 Mbps	Includes data formatting overhead
Real-time Downlink	yes	As data is acquired, it can be downlinked in near realtime (small delay needed for buffering)

RALCam-5

Parameter	Value	Comments
Mass		
Camera	220 kg	Includes margin
PCMU	26.5 kg	Includes margin
Power		
Camera - FPEA	120 W	Typical duty cycle is 10%
PCMU - imaging	87 W	Typical duty cycle is 10%
PCMU – imaging & downlinking	95 W	Typical duty cycle is 10%
PCMU – downlink only	64 W	Typical duty cycle is 10%
PCMU – data retention	0 W	
Camera Envelope		
Length	1.95 m	Does not include MLI
Height	1.25 m	Does not include MLI
Width	1.38 m	Does not include MLI
Camera Parameters & Performance		
Pan CCD pixel size	10 μ m x 10 μ m	
Number of Pan pixels across track	32,868	Based on 8 CCD devices with 4196 pixels per device and 100 pixel overlap
Number of Pan TDI stages	96	Selectable
MS CCD pixel size	40 μ m x 40 μ m	
Number MS pixels across track (per band)	8217	Based on 8 CCD devices with 1049 pixels per device and 25 pixel overlap
Number of MS band TDI stages	16	Selectable
Spectral Bands	450-700 nm 450-520 nm 520-600 nm 630-690 nm 760-900 nm	Bandwidths used for SNR calculation The MS spectral band widths can be tailored.
Focal length	10,000 mm	
Aperture	800 mm	
Radiometric Resolution	12 bits	

Parameter	Value	Comments
GSD Pan MS	0.5 m 2.0 m	At 500 km altitude and at nadir
Swath Width	16.43 km	At 500 km altitude and at nadir
Pan MTF across track	>16.1%	System level MTF - includes spacecraft velocity, bore sight jitter, thermal effects
Pan MTF along track	>10.8%	System level MTF - includes spacecraft velocity, bore sight jitter, thermal effects
Pan Signal to Noise Ratio (SNR)	>97.8	Worst case. Sun angle =80.1 deg, TDI level =96, scene reflectance = 0.3, Solar irradiance = $1500 \text{ Wm}^{-2}\mu\text{m}^{-1}$
PCMU Parameters & Performance		
Data storage	2.0 Tbit	At EOL (3 Tbit at BOL). This is typical, can be expanded to 4 Tbits.
Data output data rate to data downlink Tx's	800 Mbps	Includes data formatting overhead
Real-time Downlink	yes	As data is acquired, it can be downlinked in near realtime (small delay needed for buffering)

MDA'S HI-RES OPTICAL SMALLSATS

In addition to building the RALCam-4 and RALCam-5 optical cameras, MDA is also developing a spacecraft level product that is specifically designed and optimized for each camera. The spacecraft is in fact a part of a broader mission level product being developed at MDA that includes a corresponding ground segment that performs the spacecraft control, satellite tasking, data downlink, image processing and archiving. Together with the ground segment, the design was optimized to achieve very high image quality, and very high reliability with a 7 year mission lifetime, that is achieved at an unprecedented price point for this performance class.

The spacecraft design for the RALcam-4 is shown below in Figure 4.

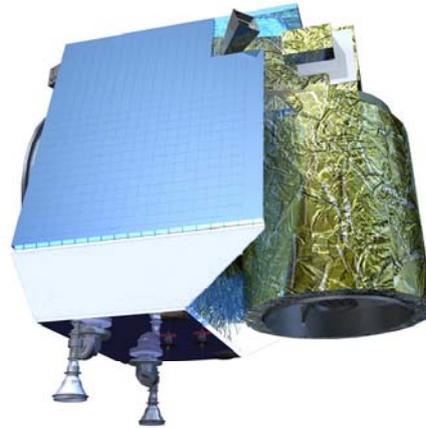


Figure 4: MDA's 1.0 m Class Spacecraft

The spacecraft design uses much of the heritage bus hardware from the 5 satellite RapidEye constellation (scheduled to launch this summer), augmented to provide higher downlink data rates, a higher performance attitude control system, increased jitter isolation and increased power. The spacecraft design allows meeting the power requirements with fixed solar panels (on three sides, +X, -X and -Z) which helps to reduce the cost and reduce the moments of inertia which allows for high agility without resorting to expensive and high power consuming control moment gyros. The compact design also enables a cold gas propulsion system to be used at 600 km to achieve the 1.0m GSD performance with ample margin for a 7 year lifetime. An option has also been included in the design for a hydrazine propulsion module that replaces the cold gas propulsion module that allows flying the spacecraft at 480 km altitude to achieve 0.8 m GSD performance and maintaining the 7 year lifetime. Also to maintain high reliability, the spacecraft is fully redundant with a mix of cold redundant hardware and graceful degradation if a unit fails. The design can tolerate a failure without significantly compromising the performance.

The key system level performance parameters are as follows:

Table 3: MDA 1.0 m Optical Spacecraft Performance

Parameter	Value	Comments
Spacecraft Mass	366 kg	Includes Xenon propellant
Spacecraft Size	1.5 m x 1.3 x 1.45 m tall	
Orbit Average Power	100 W	
Downlink data rate	420 Mbps	Includes data formatting overhead

Parameter	Value	Comments
Pointing control accuracy	0.008 deg (1-sig)	
Systematic Accuracy of image products (at nadir)	7.0 m (1-sig)	After ground processing, with NO ground control points
Precision Image Product Accuracy (at nadir)	1.2 m (1-sig)	This uses ground control points in the image processing. Assumes 5 GCP's.
Max imaging strip length per orbit	4000 km	Can image in strip mode or in spot image mode
Broad Area Coverage	>450,000 km ² / day	With 1 northern ground station (e.g., Svalbard). Can do >1 M km ² / day with sufficient ground stations.
Stereo Imaging	25 km x 80 km	Can perform up to ~45 times per day
Area Imaging	85 km x 100 km	Performed by imaging three parallel strips beside each other on the same pass

The spacecraft has been designed to be very compact to allow using low cost launch options and to allow for launching several together on one medium sized launch vehicle (such as a DNEPR). As an example, Figure 5 below shows the spacecraft in a Falcon-1E fairing with enough space and mass margin remaining to even allow for a dual spacecraft launch option (would require a custom DPAF structure from Space-X). This example is given to show that the spacecraft design allows for very low cost launch opportunities.

A similar spacecraft design is also being developed for the RALCam-5 camera. In this case, due to the size of the camera, the bus configuration allows for the camera to be oriented vertically in the launch vehicle (as oppose to horizontally as it is done with the RALCam-4 camera). The bus is designed to interface to the camera through a similar camera support frame as used on RALCam-4 so that the bus is on one side of the telescope tube. Although, in this case, the camera support frame and the corresponding bus structure tends to “wrap around” the telescope tube to be more compact. The total spacecraft length remains only slightly longer than the camera length. The 0.5 m GSD spacecraft is designed to fit into a standard 92 inch fairing for a Taurus or Minotaur IV launch vehicle and has a total mass of around 750 kg. The compact design also allows for launching 4 together on a Falcon-9 launch vehicle.

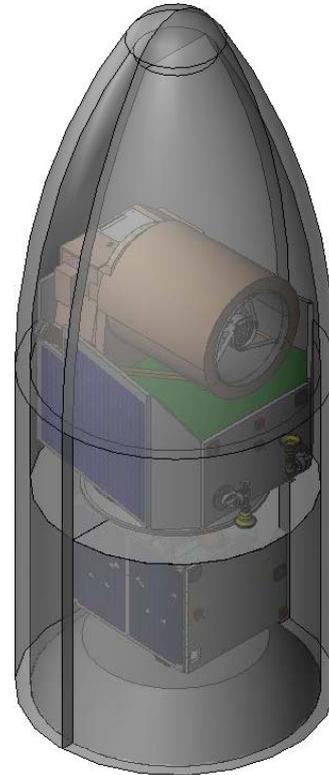


Figure 5: MDA’s 1.0 m Spacecraft in the Falcon-1E Fairing in a Dual Spacecraft Manifest Configuration

CONCLUSIONS

MDA’s high resolution optical system technology has been described. The key aspect of this technology is that it is able to achieve world class optical image quality and system performance at a fraction of the price for systems with competing image quality and operational performance and lifetimes. The key price point enablers are as follows:

1. Use of the AO³ system and optimized optics design to perform in-orbit optical alignment. This enables using conventional low cost manufacturing techniques and materials without compromising performance.
2. The integrated focal plane and Front End Electronics design in the FPEA which has been optimized to have a very low recurring cost but maintain exceptional data quality.
3. The PCPMU design which leverage MDA’s long experience in high speed electronics and experience in use of Flash memory devices

that provides a very high storage capacity at very low orbit average power.

4. MDA's established and proven processes in appropriate use of commercial EEE parts that are fully qualified in a highly cost effective manner.
5. Highly compact camera design and compact spacecraft design enables low cost launch opportunities and high agility with conventional reaction wheels.

The camera and spacecraft systems are progressing in their development and may be launched as early as 2010. Once demonstrated, we are confident this will change the economics of high resolution optical remote sensing.