Operational Class Smallsat System for Sub-Metre Resolution Imaging

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ABSTRACT

MDA, together with its UK partner RAL, has been developing its next generation of operational class smallsat sub-meter imaging systems. This development will provide an operational half-meter class solution with long lifetime and world class image quality at a dramatically reduced price point. To achieve this, MDA is leveraging heavily from the recently launched RADARSAT-2 and RapidEye missions, and also from the technology developed for the Topsat mission launched in 2005. The system contains a number of innovations that are in the process of being patented.

This paper describes the unique camera and associated satellite design that is under development to provide 0.5 m GSD from 500 km altitude. This includes an Active On-Orbit Optics (AO3) system to actively align the optics in space, and a jitter suppression system. The spacecraft bus is configured around the camera to make it compact, while providing easy access to the subsystems. Its size allows it to be launched on low cost launch vehicles, either single or a constellation. Its small size provides for high agility using conventional low-cost reaction wheels. MDA's experience in the ground systems for sub-meter class images for both DigitalGlobe and GeoEye ensures that the system will provide exceptional image quality.

INTRODUCTION

MDA has been developing high-resolution Earth Observation systems in the Radar and Optical domains. The systems cover the entire data chain from developing and operating the space segment, through development and operation of the ground segment, and data reception and processing of the finished customer's products.

As a further development of the currently operational RADARSAT-2 and RapidEye satellites, and MDA's optical one-meter class satellite, MDA has developed a half-meter EO satellite, based on the RALCam-5 electro-optical telescope.

This satellite will provide 0.5 m GSD PAN from orbit, with exceptional image quality but at significantly lower price points than currently available camera systems that offer similar data quality. The satellite platform design to go with the telescope has been progressed to the point where price and performance metrics have been defined.

The payload consists of the following three main elements:

1) The RALCam-5 electro-optical camera, which includes the telescope and an integrated Focal Plane and Electronics Assembly (FPEA).
2) The Payload Controller, Processor and Memory Unit (PCPMU) which performs all the camera control, data storage, and data formatting.
3) The Data downlink system, containing the high-speed X-band data transmitters and their gimballed horn antennas.

Figure 1: Half-Meter Satellite with RALCam-5

To help achieve the low price point, the RALCam-5 camera, the PCPMU and many of the bus subsystems share the same or similar designs and components to the previous MDA missions. For example, the PCPMU is an extended version of the version used for the 1-m class spacecraft that uses the smaller RALCam-4 camera, but now with more memory. The FPEA is also designed to be the same between these two camera systems with the exception that for the smaller RALCam-4 1 m camera, some of the CCD devices are not required so are removed. .

The RALCam-5 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.

SPACECRAFT LAYOUT

Overall Layout

The bus for the RALCam-5 camera is designed to optimally support the telescope, while providing for a small physical package, and allowing easy access to all subsystems and the camera during ground processing.

The overall size of the spacecraft was driven by the requirement to be able to launch a single satellite in a 92 inch- class fairing (e.g., Minotaur-4). The satellite has a wet design mass of about 760 kg.

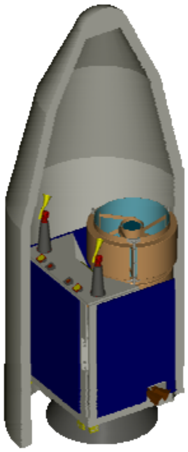

Figure 2: Half-Meter Spacecraft in Minotaur-4 Fairing

Several of the spacecraft can be accommodated in a Falcon-9 fairing: four of them can be situated next to each other in a fairing with a 4.6 meter usable diameter for a constellation launch.

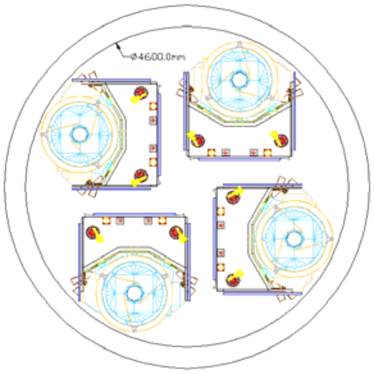

Figure 3: Four Spacecraft in Falcon-9 Fairing

Telescope Mounting

The telescope is in itself a strong structure, made from CFRP. To avoid any stresses from temperature variations in the bus from straining the telescope, the camera is mounted on an intermediate frame using titanium flexures. These flexures isolate both mechanical strain and thermal flux between the bus and the telescope. Additionally, the support frame is mounted to the bus using elastomeric vibration dampeners, which limit bus-induced jitter. This jitter isolation allows a high MTF to be maintained, while allowing a simplified design for the wheels and other moving parts on the satellite. For launch the elastomeric mounts are bypassed by launch-locks. The intermediate frame is made of the same CFRP that the telescope is made of, and the thermal blankets cover both to keep any temperature differences between the frame and the camera to a minimum. With the larger size of the camera compared to RALCam-4, the frame is now folded, to provide a wrap-around design. The additional reason to fold the frame, and remove the extended corners of the main frame of the telescope, is that the camera is launched with its optical axis in the launch direction. RALCam-4 is designed to be launched with the optical axis at 90 degrees to the launch direction.

Figure 4: Wrap-Around Support Frame, Showing Position of Star Trackers and Gyros

The integral camera support frame is also used to accommodate the star trackers and gyros that are used for the spacecraft attitude control and image processing. 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, while removing the need for the bus to be very stable. It also makes pre-launch alignment and in-orbit calibration simpler, and provides for good long-term stability.

Bus Structure

The bus structure starts with a circular launch vehicle attach fitting. This ring-shaped structure connects to the satellite base plate. This is a thick aluminium honeycomb sheet, which in turn supports an upright folded frame to which the intermediate supports and the camera are mounted.

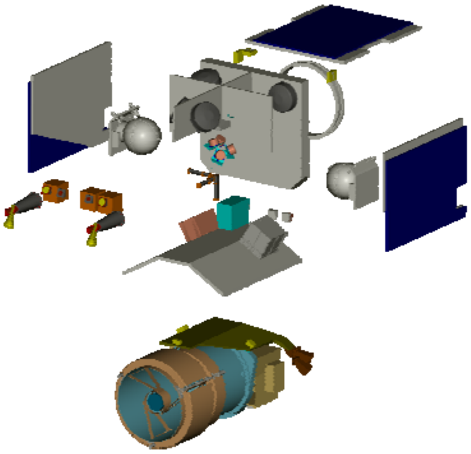

Figure 5: Exploded Satellite View

The various satellite subsystems are mounted to the intermediate frame, and to the folded support frame. The propellant tanks are mounted halfway up the structure, to be located near the spacecraft's centre of gravity and centre of pressure. This ensures that while the tanks empty out over the life of the mission, the attitude control system does not have to deal with very large offset changes between the CoG and CoP.

The Earth-facing panel, near the telescope's aperture, contains the various antennas for TT&C and the gimballed horn antennas for the high-speed data downlinks.

Mass Budget

Subsystem	Mass incl margin
Payload total (kg)	292.96
RALCAM-5 Camera	231.00
PCPMU	27.83
X-band downlink system	20.61
Gyro	5.50
Star tracker	8.02
Bus total (kg)	467.47
ADCS	51.00
Navigation	2.23
Power	107.67
TT&C	3.63
OBDH	2.52
Propulsion	91.42
Thermal	11.00
Structure + harness	198.00
TOTAL	760.43

BUS SYSTEMS

TT&C

Command and monitoring of the satellite is based on simple S-band communications, using cold redundant transmitters, hot redundant command receivers and omni antennas.

Power

Electrical power is generated by three body-mounted solar panels, containing triple-junction GaAs solar cells. The power is stored in a Li-Ion battery pack, and distributed round the satellite at a nominal 28 V. Keeping the solar arrays body-mounted reduces cost and risk, and avoids flexibility that could lead to jitter issues.

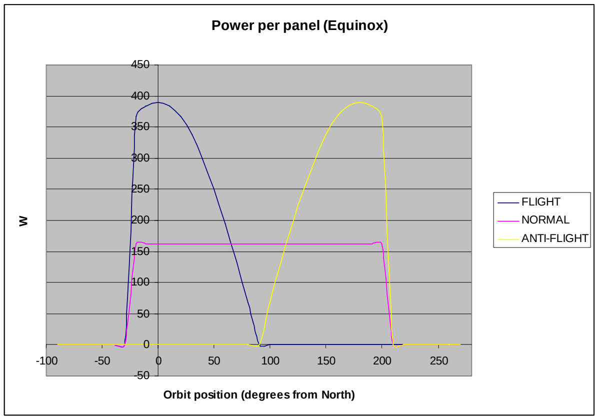

Figure 6: Power Generation per Solar Panel

The solar panels provide about 240 W Orbit Average Power (OAP) in a typical 500 km, 10:30 AM Sun synchronous orbit.

On-Board Data Handling

With the PCPMU providing all the camera control and image data handling, the spacecraft bus mainly has to deal with attitude control during the imaging. Whereas this is a non-trivial task, it does not require extraordinary processing capabilities.

For low-level data communication between the on-board computers, the various bus subsystems and the payload the satellite uses a redundant CAN network.

Attitude Determination and Control

Coarse attitude is determined by Sun sensors and magnetometers. During imaging operations the satellite uses the star trackers and gyros to determine accurate attitude. Four star trackers heads are used (see Figure 4) to provide both greater redundancy but also improved systematic accuracy. This information is also combined with the imaging data to allow post-processing of the images.

The attitude is controlled by a combination of two sets of four wheels. The set of larger wheels is used solely to provide for quick slews between images. The slew algorithms are designed to ensure that the large wheels are at a complete stand-still during imaging, with only the smaller wheels controlling the attitude during actual image take. It turns out to be no small matter to design the algorithms for this double wheel configuration, and the analysis for ensuring that the wheels come to a complete stop quickly after the slew manoeuvre, without upsetting the stability of the satellite, would take too many pages to be included in this paper. The solution uses a combination of dead-reckoning, tacho feedback, and predicted friction to provide for appropriate slew design.

The larger wheels have therefore no requirements for low jitter (e.g., torque ripple, bearing noise). The smaller wheels have naturally lower jitter, and they are fitted with tuned elastomeric dampeners so that any jitter is further reduced. This design was developed and is now in use for the RapidEye mission MDA was prime contractor for, that launched in August 2008 and is now in full operation. The optical telescope is also mounted on elastomeric dampeners, reducing any jitter even further, ensuring that the camera's MTF remains within specification.

Three redundant magnetorquers are used to offload excess momentum from the wheels.

The spacecraft is not limited in off-pointing angle, although for long-time stability at least one of the star trackers should be looking at a suitable part of the sky. This off-pointing capability allows the satellite to track the Moon, and use its visual signal to calibrate the optical performance of the imager.

Due to the compact spacecraft size and low mass, the spacecraft has very high agility using conventional reaction wheels (i.e., no CMG's). A 300 km slew can be performed in < 14 sec. With this level of agility, the spacecraft can point the telescope to take images in a number of different modes:

Strip Imaging: Takes long single image strips up to 4000 km long per orbit.

Stereo Imaging: Perform in-line stereo image pair acquisitions that are up to 120 km long.

Area Imaging: Perform manoeuvres to acquire triple width images that are 55 x 120 km in size.

Spot Imaging. Acquire up to approximately 30 spot images per orbit (16.4 km x 16.4 km) in different locations within the field of regard of the satellite.

Orbit Control

The projected orbit of the satellite, at 500 km altitude, requires the inclusion of a propulsion system to maintain the altitude, and, in turn, the Sun angle of the Sun-synchronous orbit.

The system uses two tanks of 35 kg of mono-propellant hydrazine, each tank feeding two redundant thrusters. The two propellant tanks are each mounted on an integrated panel that also houses the controller, the thrusters, valves and sensors. This allows those subsystems to be fully assembled separately without the need for plumbing operations with the satellite structure.

OPTICAL CAMERA

Optical Path Design

The RALCam-5 optical design is an expansion of the RALCam-4 telescope layout. It is a similar Korsch TMA design, containing three power mirrors and two flat folding mirrors to make a compact five-mirror optical path. The mirrors are made of lightweighted Zerodur, and they are coated with aluminium.

The main mirror (M1) is mounted on a central CFRP frame. On this same frame the CFRP metering tube is mounted, which holds M2 and the alignment mechanism. M3, M4 and M5 are mounted on the rear of the main frame, in a box structure that also holds the FPEA and thermal radiators.

The optical design gives near diffraction-limited performance over the entire field of view. An added advantage of this design is that there are no transmissive elements (lenses) in the optical path, removing any chromatic aberration. This means that the sensors for the various colour bands do not require individual focussing and alignment.

The first mirror is a conic of 750 mm diameter, reflecting onto a second mirror that is mounted in the metering tube. The image is passed through a hole in the main mirror, and folded by the first flat mirror onto the third active element. A second flat fold mirror redirects the focussed image on the array of CCD sensors. The system forms an intermediate image between M2 and the first fold mirror, and an exit pupil between M3 and the second fold mirror. This allows effective placement of baffles for stray-light rejection.

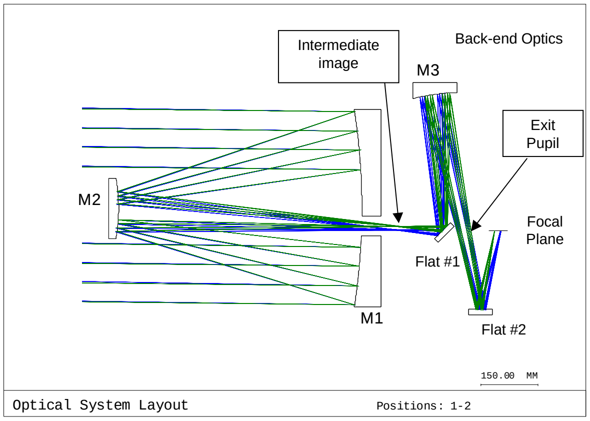

Figure 7: RALCam-5 Optical Path

The focal length of the optical design is 10,000 mm, which, coupled with the 10-micron size of the CCD pixels, gives 0.5 m GSD at Nadir from a 500 km orbit in the PAN band. The multi-spectral bands use 40 micron pixels for 2 m GSD in four bands.

SNR

The PAN SNR, after taking TDI into account is calculated to be as follows:

SNR:	>98
Sun angle:	80.1 deg
TDI level:	96 (PAN)
scene reflectance:	0.3
Solar irradiance:	1500 Wm-2µm-1

Active On-Orbit Optics (AO^3) System

A critical design aspect of the RALCam-5 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 (e.g., water vapour loss) or thermally induced deformations. The high positional stability of the optical elements can be a major cost driver. This issue is addressed in both the RALCAm-4 and RALCam-5 cameras by the implementation of active optics. This system allows in-orbit correction of the camera alignment, thereby reducing reliance on stability of the design. The AO^3 system is used to re-align the telescope following launch, using proprietary techniques to define the adjustment parameters and analyse the results. The optics design has been carefully selected and optimized to allow for a simple realignment scheme to maintain high reliability and low cost. 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 Modulation Transfer Function (MTF), the AO^3 system can re-align and focus the telescope to recover to very near pre-launch performance. This is demonstrated in Figure 8 that shows the initial MTF after large misalignments and the corrected MTF after the AO^3 system was used for 2 iterations (i.e., two successive corrections).

MTF

The Modulation Transfer Function of the camera is the main metric for assessing the alignment of the telescope.

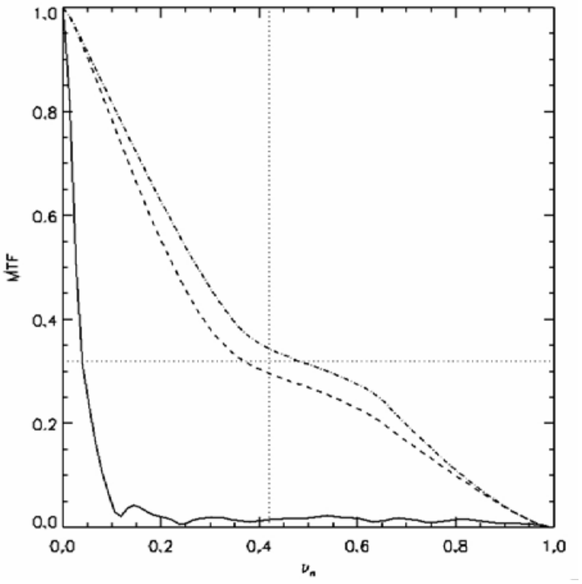

Figure 8: Calculated MTF Before (Solid Line) And After AO^3 Correction (Dashed Lines)

The system MTF across track is greater than 16.1 %, calculated from 38% nominal optical design MTF, corrected by a factor of 0.637 because of CCD geometry, and a factor of 0.665 covering across-track jitter, thermal gradients, manufacturing imperfections, etc.

The system MTF along track is greater than 10.8 %, from the same 38% nominal, corrected by factors of 0.637 and 0.446, respectively, as above.

Focal Plane and Electronics Assembly (FPEA)

The CCD array uses several individual detectors for each colour band, (Red, Green, Blue, NiR and PAN), creating a push-broom sensor. Each colour uses an optical band-pass filter to define the response of the particular channel.

The CCDs are of TDI (Time Delay Integration) type. This TDI allows multiple-step integration of the optical signal (up to 96 steps), to drive the system SNR. The diameter of the aperture is therefore only driven by the requirement of maintaining an acceptable MTF.

The FPEA uses two different CCD detector designs, one customized for the panchromatic band, and one custom designed 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 (adjustable) TDI lines. The number of active TDI steps can be changed by command to tune the sensitivity of the imager.

Each individual CCD sensor has four output amplifiers to provide the required 15 MHz line rate for the application.

For the multi-spectral sensors, each chip package contains four separate TDI devices, spaced 1.5 mm apart on one overall piece of silicon. Each TDI sensor area is covered with an optical filter, providing the appropriate bandpass characteristics. The multispectral pixel size is 40μm square, with 1049 columns and 16 levels of TDI. The data rate per line from each of these devices is 1/16th of the data rate of the PAN sensors, allowing the use of only a single output amplifier per sensor.

The complete focal plane layout for the RALCam-5 FPEA includes 8 devices with PAN CCD chips in a staggered configuration with 100 pixel overlap for each of the segments, and a similar array next to it of 8 Multi-spectral devices with 25 pixel overlap each. Note that for the smaller RALCam-4 camera, only 5 of the PAN and MS CCD devices are used.

The Front-End Electronics (FEE) is packaged together with the focal plane in the FPEA for close electronic proximity, but it is thermally decoupled.

Video processing ASICs are used that provide pre-amplification, Correlated Double Sampling (CDS) and analogue-to-digital conversion (ADC) of the analog 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 multi-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 and 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 and to send the telemetry data.

Four FPGAs are used to transmit the digitized video data out of the FEE over a number of high-speed serial data links. 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 ground commands to use the redundant set of I/O interfaces.

Image Quality

The predicted image quality has an estimated NIIRS Rating of 5.3 on the panchromatic scale, and 5.85 on the multi-spectral scale. This is based on the General Image Quality Equation (GIQE).

The expected systematic geolocation accuracy is 10 m (CE90) using no Ground Control Points (GCP).

After GCP inclusion in the image post processing and analysis, the expected Precision Product Accuracy is 2.3 m (CE90).

Thermal Design

The camera is designed to provide for a simple thermal control scheme. Thermal control of the camera is achieved by a combination of electrical heaters and a passive radiator that mounts directly to the rear of the camera. The radiator is located near 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 and 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.

PAYLOAD CONTROLLER, PROCESSOR AND MEMORY UNIT (PCPMU)

The PCPMU for the half-meter mission is a version of the general purpose, modular design that can be used in a wide variety of missions. Its 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 and low power, but allowing for highly competitive price points compared with other electronics systems of this class. The design is based on the developments for the RADARSAT-2 payload electronics and the Cassiope mission's 1-Terabit Data Storage Unit (DSU), which uses flash memory devices to provide non-volatile memory storage.

Important to the development of the electronics is MDA's extensive knowledge and expertise in the appropriate use of commercial parts for space. MDA has years of heritage working closely with NASA and large mission primes on qualifying commercial parts for space missions. This approach has been used successfully on 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 half-meter mission, the PCPMU provides the following main functions:

- Instrument Controller: The PCPMU provides the direct control signals to the camera to control the operating parameters and image timing. It also provides the interface to the bus and interprets the high level commands to execute the various operational modes.
- Optical Instrument Data Interface: It accepts high speed image digital data from the optical camera. The unit can accept data at total speeds of up to 10 Gbps.
- Image Compression: the optical image data can be compressed in real time using JPEG2000, with variable compression level settings.
- On-board Memory: 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 two parallel IQC channels to the two downlink transmitters at data rates of 400 Mbps per transmitter.
- Mechanism Drive Electronics: The unit provides drive signals to control the X-band data downlink antenna gimbals as well as the AO^3 mechanisms on the camera that are used for optical alignment.
- Power Control: The PCPMU has an internal power controller, taking unregulated 28V from the spacecraft platform, providing various secondary voltages and switches for the internal modules and instruments.

The PCPMU consists of an aluminium machined enclosure, housing a series of standard 6U (eurocard) cards. The cards are wedge locked into the chassis for easy assembly, and the back-plane design reduces the number of wired connections between the boards.

The PCPMU is internally redundant with at least two 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, and provide additional mechanical stiffness. The PCBs slide into the housing to mate into the backplane. They are then held in place using card-lock retainers. The backplane is designed to isolates EMC between the power and signal lines.

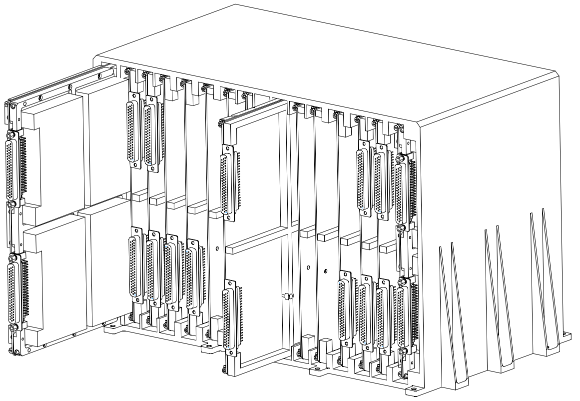

Figure 9: PCPMU Assembly (cover removed)

CAMERA SPECIFICATION

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 10%
PCMU - imaging	87 W	Typical duty cycle 10%
PCMU – imaging & downlinking	95 W	Typical duty cycle 10%
PCMU – downlink only	64 W	Typical duty cycle 10%
PCMU – data retention	0 W	

Parameter	Value	Comments
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	10µm	Square
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	40µm	Square
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	750 mm	
Radiometric Resolution	12 bits	
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 Wm^{-2}µm^{-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)

CONCLUSIONS

MDA's half-meter optical satellite has been described. The key aspect of this design 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. Integrated design of the camera and satellite structure. The use of the folded camera support frame, together with the wrap-around bus structure (both designed in-house) makes for a small, easy to build and launch, and therefore low-cost solution.
2. Satellite design based on available low-cost launch vehicles. The overall size of the spacecraft fits inside standard fairings.
3. Low power design allowing low-cost, low-risk body-mounted solar panels.
4. Dual wheel set attitude control. Using large wheels for large slews between images, and small, low jitter wheels that are mounted on vibration isolators for imaging.
5. Use of the AO^3 system and optimized optics designed to perform in-orbit optical alignment. This enables using conventional low cost manufacturing techniques and materials without compromising performance.
6. 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.
7. 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.

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

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