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A 1m Resolution Camera for Small Satellites

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Abstract: The paper will describe how the performance of RALCam-1, the camera flying on TopSat, which is achieving 2.8m resolution at 686km altitude, has led to the development by the Rutherford Appleton Laboratory of an advanced, low cost, low mass, 1 meter resolution camera for small satellites. This camera, now under development, will fly at 600km on a small sat further advancing the scope for affordable constellations of high resolution imaging systems. The paper will concentrate on the innovative approach of the camera and how it will overcome the problems of stability of the optical bench through launch and in the thermal environment of space. It will describe the challenges and solutions related to the data dissemination and storage for such a high resolution pan and colour imager. We will end by describing how these developments will be exploited through technology transfer into the commercial sector.

INTRODUCTION

In October 2005 the TopSat spacecraft carrying a high resolution remote sensing camera was launched from the Plesetsk launch site in Russia. Since then it has been operating successfully, taking over 500 2.8m and 5.7m ground sample distance (GSD) panchromatic and colour images (see Appendix A for some example images). The success of the camera has encouraged the development of an even higher resolution imager that can delivery 1m GSD imagery, but still be compatible with small satellite platforms. The technology used for the TopSat camera will be applied again to the 1m camera, but the challenges of keeping the overall mass and volume to a minimum will probably require active control of the mirrors or focal plane. This paper describes some of the design aspects of a prototype 1m camera currently under development at the authors' institute.

1M CAMERA SPECIFICATION

The specification for the 1m camera was derived after discussions with small satellite providers. Their main requirements were for a camera capable of producing 1m imagery from a platform operating at an altitude of 600km, with a mass of less than 50kg, and a volume that would permit up to three spacecraft/cameras to be launched at a time using a low cost launch vehicle, such as a Kosmos 3. The emphasis was very much on small volume, low mass and power, and low cost. One important requirement was that the camera should not be dependent on the spacecraft using a Pitch Compensation Manoeuvre (PCM) to increase the signal-to-noise ratio in the detector. A large number of wavebands was not a high priority, but both panchromatic and near infrared were desirable.

OPTICS DESIGN

In designing the optics for the camera we took into consideration a number of factors, of which the primary one was to keep the overall volume of the camera compatible with small satellite platforms. Indeed, one option was to consider building the spacecraft around the camera primary structure creating a more integrated and efficient design. After much iteration the optical design shown in Figure 1 was selected as the most promising. It is a classic Ritchey-Chrétien design with a fused silica corrector group located behind the primary mirror.

The requirement for a large aperture has been minimised through the use of Time Delay Integration (TDI) CCD detectors so the aperture is now sized to reduce diffraction effects only. The image plane has been optimised to accommodate four linear CCDs spaced approximately 25mm apart, allowing four bandwidths to be selected through the use of precision bandpass filters placed in front of the detectors. The distance between the secondary mirror and the image plane is of the order 1100mm, leading to an overall camera length of approximately 1500mm. The diameter of the camera, dictated by the size of the primary mirror, is approximately 550mm.

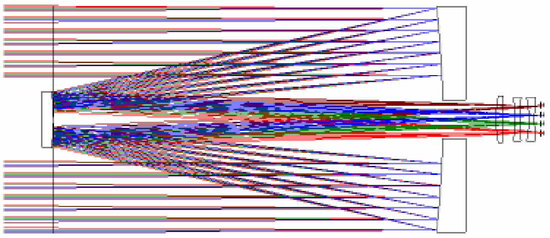

Figure 1. Optical Layout

The image quality is presented in Figure 2, and shows the MTF performance for the blue channel at different field angles. The Nyquist frequency of the camera is 62.5 lp/mm.

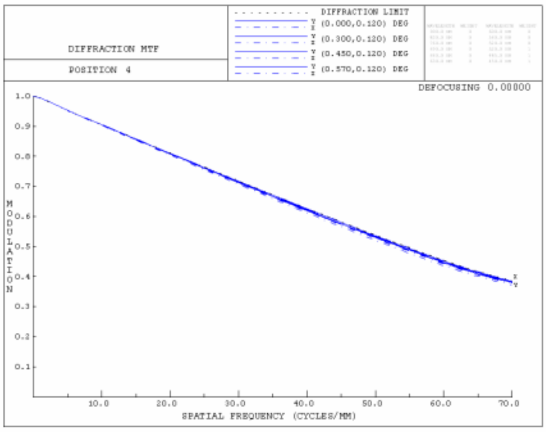

Figure 2. MTF Performance for Blue Channel

DETECTOR ELECTRONICS

The focal plane contains four TDI CCD arrays with filters for Blue, Green, Red and NIR bands. Each array provides a swath of 12,228 pixels and 96 selectable TDI stages. The selectable stages provide on-chip gain control and thus enable the camera to operate to optimal performance over a wider range of illumination conditions. The pixel size is 8 µm x 8 µm. The 12,228 pixels are read out through eight output amplifiers capable of 15 MHz operation.

At 600 km altitude, the time taken to travel 1 m (or 1 pixel) is 145 µs and it follows that the pixel readout rate through each of the eight output amplifiers must be greater than 10.6 Mpixels/s. Assuming that, before any compression, the pixel data is contained within 2 bytes, then the data rate for each output amplifier is greater than 21.2 Mbytes/s.

We plan to serialise the data and transmit it to a data handling unit (DHU) using the SpaceWire protocol with one link per output port and a link speed in excess of 212 Mbits/s. Eight links are required for each CCD and hence a total of 32 links are needed for the 4-band focal plane. The overall data rate from the focal plane array is 167.2 Mbytes/s per band or 668.8 Mbytes/s for the four bands.

The time taken for the camera to integrate a square image of 12,228 x 12,228 pixels is 1.77 seconds, and the data collected from the 4 bands amounts to 1.196 Gbytes.

STRUCTURE DESIGN & ANALYSIS

The structural design uses heritage from the TopSat camera in that it makes use of a low coefficient of thermal expansion (CTE) Carbon Fibre Reinforced Polymer (CFRP) material. By careful choice of the lay-up it is possible to achieve a CTE near to zero over the temperature range likely to be encounter on orbit. The stability requirements on the structure are extremely demanding, with the M2 mirror required to remain at its optimal position to within 4 microns following ground based testing and through launch. To help relax this requirement it is necessary to fit a mechanism that will allow for some form of re-positioning of the mirrors or focal plane assembly to provide on-orbit correction of the image quality. The proposal is to fit three piezoelectric actuators to the front end of the metering tube controlling the spacing and rotation of the secondary mirror (M2) relative to the primary. The actuators will allow the whole M2 assembly to be adjusted in three degrees of freedom providing more options for correcting the image quality than just a refocusing mechanism. The advantage of moving the whole front end of the camera is that the actuators can be placed outside of the aperture and will therefore not contribute to the obscuration of the system. The actuator concept is shown in Figure 3. The basic design of the camera can be see in Figure 4.

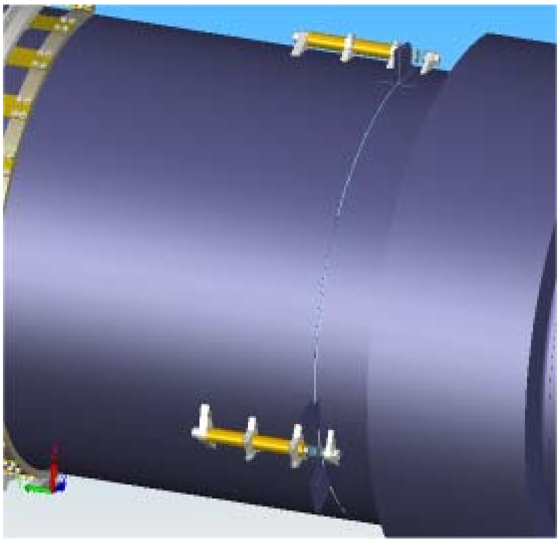

Figure 3. Actuator Concept

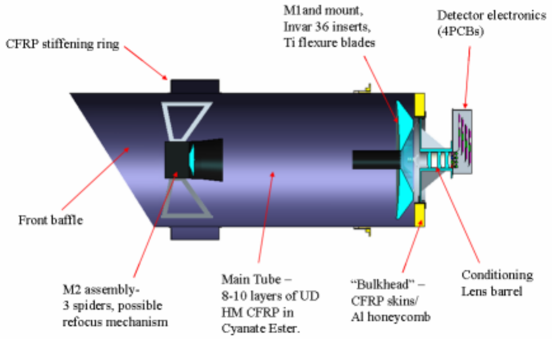

Figure 4. Section through Camera

The primary structure consists of a main bulkhead to support the primary mirror, lenses assembly and focal plane electronics. The secondary mirror is spaced from the primary by a metering tube, with the mirror itself supported from a spider frame. All of the main structural elements are made from CFRP. One challenging aspect for the camera structural design is how to provide a strain free mounting to the spacecraft. With the premise that the spacecraft should be built around the camera, it is important to prevent the loads from the spacecraft subsystems from passing through the camera. One proposal under consideration is to attach a ring of flexures around the main metering tube, at a position along the camera's axis corresponding to its centre of mass. The flexures will allow radial movement between the camera and spacecraft whilst providing high stiffness in the axial direction. This arrangement has been analysed using a finite element model and has shown to be successful at providing a high first natural frequency for the camera (see Figure 5.)

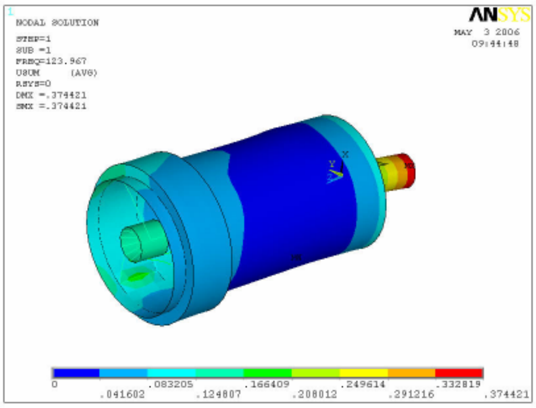

Figure 5. 1st Structural Mode of Camera

The design of the camera structure, and M2 actuators, are key to the success of meeting the image quality requirements, and so a engineering model of both these items will be manufactured and tested to de-risk the flight model programme.

PRIMARY MIRROR DESIGN

One of the largest components of the camera is the primary mirror. At just under 500mm in diameter and made from low expansion Zerodur, a blank 85mm thick (using the 1:6 rule) would have a mass of 45kg. For a low mass camera this would be unacceptable, so extensive lightweighting of the mirror is required. Several optics manufacturers were approached and asked to provide information on their techniques for producing lightweight mirrors. Table 1 shows a comparison of the primary mirror mass for different lightweight options.

Table 1. Mirror Options

Method	Mass (kg)	% L'weight
Honeycomb	15.8	65
Pocketing	10.0	77
Double arch	22.0	51

The high degree of lightweighting possible with Zerodur mirrors, and the low density of CFRP, means that the 1m camera is predicted to have an all up mass of less than 40kg (excluding the data storage unit). This is well within the payload limit of current small satellites.

THERMAL ANALYSIS

A thermal analysis of the 1m camera was undertaken to estimate the likely temperature gradients in the primary structure, and the heater power needed to maintain the camera at its nominal operating temperature of 20 °C. The assumptions were that the camera was mounted inside the spacecraft structure (see Figure 6) and the boundary nodes (i.e. spacecraft subsystems) were at a constant 22 °C. The nominal orbit case is a 600km, sun synchronous orbit with right ascension 1030hrs.

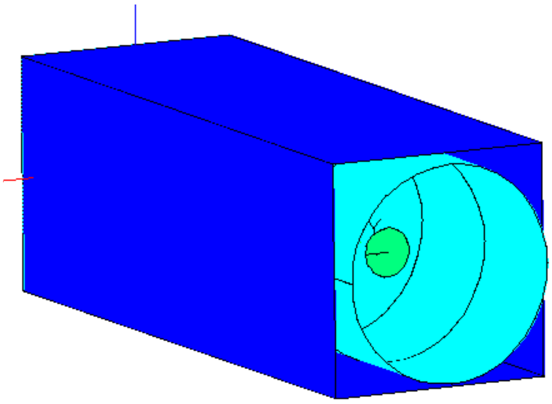

Figure 6. Geometric Model for Thermal Analysis

The temperatures of the camera subsystems, without any thermal control applied, are shown in Table 2.

Table 2. Temperature Predictions

Node	T min (deg C)	T max (deg C)
Camera casing 1	21.80	21.87
Camera casing 2	20.79	21.66
Camera casing 3	20.09	21.53
Camera casing 4	18.07	21.81
Camera casing 5	9.04	25.90
Camera casing back plate	21.86	21.90
Primary Mirror	21.69	21.78
Secondary Mirror	7.59	19.77
FPA	21.78	21.82

The power required to maintain the secondary mirror at an operational temperature of 20°C was calculated for the steady-state hot, cold and nominal cases. This was achieved by calculating the energy lost from the mirror whilst being fixed at 20°C. The results are shown in Table 3.

Table 3. Heater Power

Orbit Case	Power required (W)
Cold Case (12°C)	0.39
Nominal Case (22°C)	0.24
Hot Case (32°C)	0.07

Ideally no heater power should be needed to maintain the camera at its working temperature, but clearly some thermal control of the camera will be needed. If the camera is mounted externally to the spacecraft platform, then more heater power would be needed to maintain its operating temperature and reduce thermal gradients along its length.

TECHNOLOGY TRANSFER

The high risk nature of developing new products for space has meant that businesses have not been willing to invest in products like high resolution remote sensing cameras. However, now that the TopSat Camera has been proven, the technology and IPR has been spun out into a commercial business with the aim of making high resolution camera available to a wider market. Orbital Optics Ltd is now actively involved in the production of a range of compact, low cost imagers and has raised investment for the development of the 1m camera described above. It is envisaged that once the 1m camera has been de-risked through developing and testing a prototype model (in collaboration with RAL), a flight model camera could be ready for procurement by early 2008 with a 23 month build phase. The low cost of this imager, together with the low cost of small satellites will make 1m imagery much cheaper than it is currently, and will certainly allow developing nations to buy and operate their own systems. The problem of achieving high swath widths can be overcome by a constellation of spacecraft flying in close formation. Because the cost of these systems will be so low, constellations will be an affordable solution to achieving short re-visit times and high global coverage.

CONCLUSION

A concept for a compact, lightweight camera capable of producing 1m imagery has been presented. The initial results suggest that such a camera could be flown on a small satellite in the near future, provided that the technical challenge of maintaining mirror stability can be overcome. Through the development and test of a prototype model camera, where the ideas presented in this paper can be tested without commercial risk, it will be possible to have a camera ready for flight within three years.

ACKNOWLEDGEMENTS

We would like to acknowledge the help and support of all our colleagues in the TopSat consortium (Surrey Satellite Technology Ltd, QinetiQ and Infoterra) for their part in making TopSat successful. Without this success the investment secured through Orbital Optics Ltd for the 1m camera development would not have been possible.

APPENDIX A TOPSAT SAMPLE IMAGES

Figure A1. Northern Australia, 8th Jan '06

Figure A3. Washington, USA, 31st Mar '06

Figure A2. Saskatoon, Canada, 15th Dec '05

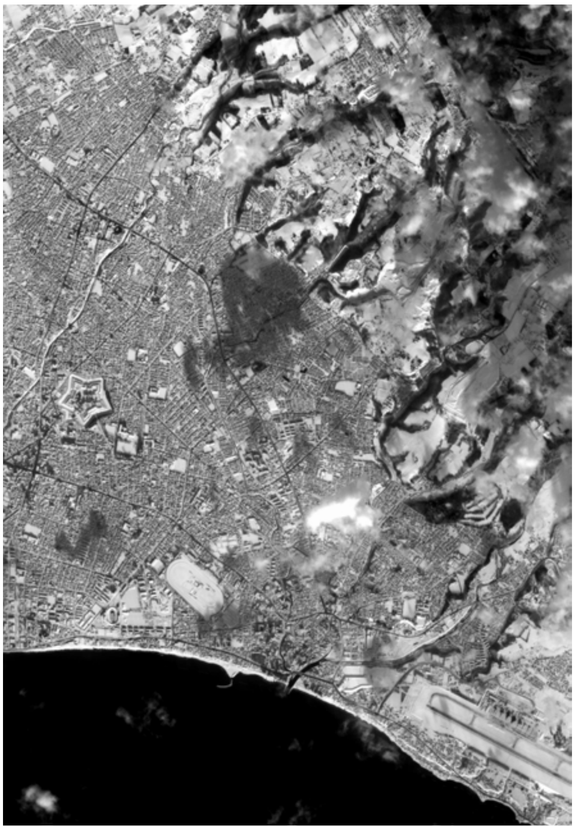

Figure A4. Hakodate, Japan, 11th Jan '06