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A HIGH-RESOLUTION MULTI-SPECTRAL IMAGING SYSTEM FOR SMALL SATELLITES

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ABSTRACT

SaTReC*i* and ATSB are developing a high-resolution imaging system for small satellites as a collaborative program. This compact and cost-effective imaging system, the Medium-sized Aperture Camera (MAC), produces images in one panchromatic and four multi-spectral bands with ground sampling distances of 2.5 and 5.0 m respectively at 685 km altitude. It weighs less than 50 kg and its peak power consumption is less than 50 W. The development of four models is planned. For the test model, the telescope whose major components are made with Aluminum is ready for integration and the electronics is being integrated and tested. Design of the engineering model is presented together with the analysis results. Design optimization is in progress and the development of the engineering model will be complete by May 2002.

1. INTRODUCTION

A high-performance micro-satellite, KITSAT-3, developed by the Satellite Technology Research Center (SaTReC) was launched in May 99 into a 730 km sun-synchronous orbit. Since its launch, its primary payload, a pushbroom multi-spectral imaging system, has produced numerous images of high quality and demonstrated the potential of micro-satellites as a cost-effective tool for earth observation.

ATSB successfully launched Malaysia's first micro-satellite, Tiungsat-1, in September 00 aboard the Russian launcher Dnepr into a 650 km orbit. Ever since, Tiungsat-1 has been returning high-quality images, which have been used for numerous applications.

Since the successful launch of IKONOS-2, the commercial market for high-resolution satellite images has substantially increased. Consequently, several commercial "big" satellites for high-resolution imaging are under development [1]. On the other hand, a new attempt is being made to provide high-resolution images using "small" satellites. EROS A1-2 that weighs 280 kg proves that such an attempt can become a valuable alternative [2]. In addition, as the cost-effectiveness of micro- or small satellites was recognized more widely, several constellation programs were suggested for environment and disaster monitoring. A forecast shows that images with 1 ~ 3 m resolution will represent almost 50% of the market share with another 25% represented by 5 ~ 8 m resolution images [3].

SaTReC*i*, a commercial venture established by key engineers of SaTReC, and ATSB are developing the next generation pushbroom imaging system for small satellites as an international collaborative research and development program. This cost-effective imaging system, the Medium-sized Aperture Camera (MAC) will become a valuable demonstration tool for high-resolution earth

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observation using small satellites and commercialization of its product.

2. PROGRAM SUMMARY

The MAC program commenced in May 00 with the formation of an integrated development team of engineers from SaTReC*i* and ATSB. This program has three prime objectives as follows.

- Development of a cost-effective high-resolution imaging system for small satellites (of 200 ~ 300 kg)
- Implementation of new technologies for future systems
- International collaboration for mutual benefit

The total program period is approximately three and half years. Four models are planned in order to reduce risks: test, engineering, qualification and flight models. According to the current program schedule, the test model will be ready by April 00 and the completion of the engineering model is planned by May 02 with qualification flight models by February and August 03, respectively.

The MAC program is a stand-alone program without its satellite bus system together with mission clearly defined. Therefore, top-level requirements were derived from previous experience for this program. The assumed mission orbit is a sun-synchronous circular orbit with the nominal altitude of 685 km and the inclination of 98.13 degrees.

3. SYSTEM OVERVIEW

As a typical pushbroom imaging system, MAC produces images with linear detectors aligned perpendicular to the satellite's velocity vector. Table 1 summarizes key features of the MAC system.

The functional block diagram of MAC is shown in Figure 1. The electro-optical subsystem (EOS) includes telescope, focal plane assembly (FPA) and signal processing unit (SPU) and the electrical and electronic subsystem (EES) does management and mass memory unit (MMU) and thermal control and power supply unit (TPU).

The telescope is a Ritchey-Chrétien type with an aperture of 300 mm diameter and the effective focal length of 1918 mm. Its optical power is shared by all detectors on the same focal plane. Within FPA, five identical linear detectors are employed for one panchromatic and four multi-spectral bands. These detectors are read out simultaneously and processed by SPU.

Imaging channels	1 panchromatic (PAN) 4 multi-spectral (MS)	
Spectral bands (μm)	PAN	0.51 ~ 0.73
	MS	0.45 ~ 0.89
GSD (m)	PAN	2.5
	MS	5.0
Swath width	≥ 20 km	
MTF (%)	PAN	≥ 8
	MS	≥ 15
SNR	≥ 70	
Signal quantization	10 bits	
Signal gain	Programmable	
Mass storage	32 Gbits (8 for EM)	
Mass	≤ 50 kg	
Peak power consumption	≤ 50 W	
Lifetime	3 yrs (20% duty cycle)	

Table 1 - Key features of MAC system

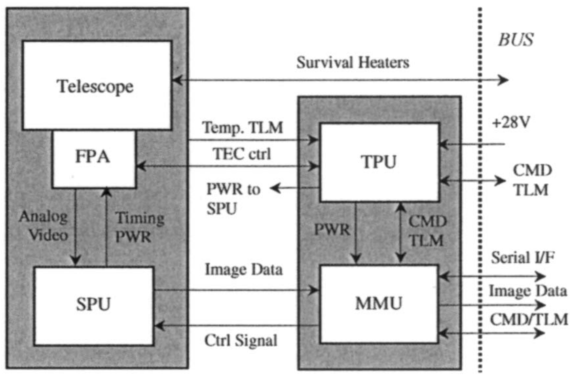

Figure 1 - MAC functional block diagram

SPU performs the off-chip pixel binning for multi-spectral signals. It eliminates the reset noise using correlated-double sampling and quantizes analog signals into 10-bit digital data. Only 8 most significant bits of the image data are multiplexed and transmitted to MMU in high speed. Offset correction and programmable gain functions are also supported by SPU.

At the heart of MMU, a high-speed processor performs the management of system operation and maintenance of memory devices. It communicates with the satellite bus via an asynchronous link for command and telemetry data. The storage module of MMU consists of modules of 64 Mbits SDRAM devices. The stored or real-time quick-look image data is transmitted to the satellite bus at 30 Mbps for X-band transmission.

TPU provides power to other units from an unregulated +28V supply of the satellite bus. The satellite bus performs the power on/off control of MMU controllers, which perform the on/off control of other units or modules. TPU also performs the thermal control of FPA by regulating the current flow through a thermo-electric cooler of FPA.

4. TEST MODEL DEVELOPMENT

The test model (TM) is a preceding system for the engineering model (EM). Its development was incorporated in the program in order to minimize risks because MAC is a completely new system both for SaTReC*i* and ATSB. Objectives of TM are as follows.

- Verification of the optical design concept and the alignment logic
- Functional test of the signal processing chain for a single detector
- Establishment of facility for telescope assembly and integration

Another objective is to test and evaluate the performance of an all-Aluminum telescope. Metal mirrors have drawn attention as an attractive alternative to glass because of its good thermal conductivity and good machinability. Compared with Beryllium or other exotic materials such as Silicon Carbide, Aluminum is not toxic, easier to handle and machine and less expensive. In addition, because many structural components are manufactured with Aluminum, an all-Aluminum telescope has its advantage for athermalization and it can be a good candidate for a cost-effective program.

4.1. Aging Experiment

An experiment was performed on the convex hyperbolic secondary mirror to evaluate its aging effect, i.e., the variation of surface figure over time. Several secondary mirror blanks were machined either into best-fit sphere or into hyperboloid and their surface figures were measured.

For spherical surfaces, several Al6061-T6 blanks were machined and one of them went through an additional heat treatment according to Vokobratovich [4]. The interferometric measurement of radius of curvature and surface figure showed they were within tolerances of ±5 mm and λ/12 RMS, respectively. Figure 2 shows the variation of surface figure of two spherical mirrors over time. The profilometric measurement of aspheric surfaces also showed that the variation of surface figure error over time was within tolerance of λ/12 RMS.

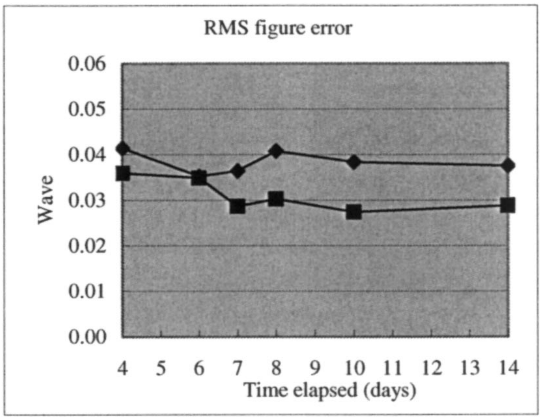

Figure 2 - Surface figure variation over time

4.2. Manufacturing and Test

Except for BK7 correction lenses, all optical and mechanical components of the TM telescope were manufactured with Al6061-T6. Figure 3 shows the finished surface profile of the primary mirror, which has a surface figure error of about λ/13 RMS.

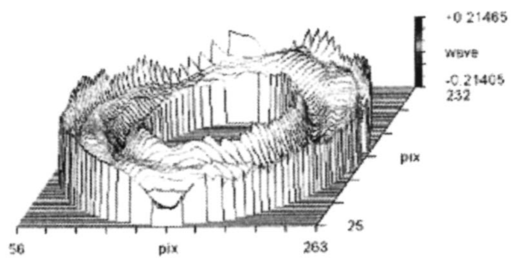

Figure 3 - Surface profile of primary mirror

Some bubbles were observed on the secondary mirror surface after electroless Nickel plating. Because the machined blank surface was smooth enough for TM, the secondary mirror was manufactured by applying Aluminum and protective MgF_2 coatings directly on the machined surface. All other optical and mechanical components are ready for assembly and integration, which is scheduled in April 00.

Integration and testing of electronics is also under progress. A personal computer (PC) is used for the real-time reception and display of digital image data from the signal processing chain. The PC interface card will be used during the integration of detector electronics to the telescope and as a part of ground support equipment for EM.

5. EM DESIGN & ANALYSIS

5.1. Optical Design

The optical design for TM was optimized for EM in order to decrease the overall length of the telescope and the number of correction lenses. The telescope consists of two hyperbolic mirrors and two spherical correction lenses as shown in Figure 4. The distance between primary and secondary mirrors is 440 mm and the clear aperture diameter is 300 mm. This design is nearly diffraction-limited with design MTF values of 31 and 60% at pixel Nyquist frequencies for panchromatic and multi-spectral bands, respectively.

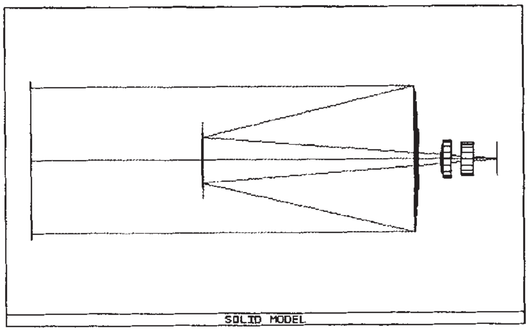

Figure 4b - Layout of EM telescope

From a detail tolerance and sensitivity analysis, various tolerance values were derived. According to Smith [5], total RMS wavefront error (WFE) less than 0.145λ is required for the telescope in the worst case. This value gives the MTF value of 16% for the telescope and 8% at system level. Figure 5 shows the WFE allocation for major elements of the telescope.

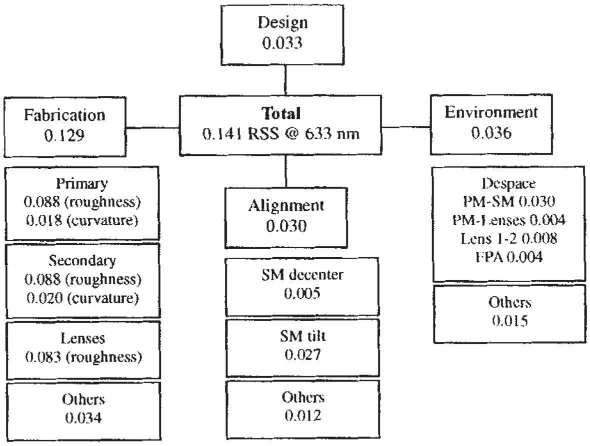

Figure 5 - WFE allocation for telescope

The obscuration ratio by the secondary mirror assembly is about 0.74. Considering energy loss from coating and transmission, the total transmitted energy is about 0.46 in the worst case.

5.2. Opto-mechanical Design

Although the variation of surface figure and curvature for Aluminum mirrors was within tolerance for TM, advantages of Aluminum mirrors in terms of fabrication time and cost were not significant compared with traditional low-expansion glass mirrors. In addition, an all-Aluminum optical system requires a rigorous active thermal control to make the most of athermalization.

For EM, therefore, the traditional approach of using low-expansion materials for critical components is implemented. Figure 6 shows the overall mechanical configuration of EOS except for the entrance baffle. It was found that the positioning accuracy of the entrance baffle is not critical in maintaining the optical performance and the baseline approach is to mount it directly to the satellite bus structure.

The primary mirror assembly consists of baseplate, solid primary mirror and flexures. The secondary mirror assembly consists of mirror housing, assembly ring and spiders. Metering rods controls the distance between mirrors. The main housing is isolated from the secondary mirror assembly and is used as a baffle structure. The correction lens assembly, FPA and SPU are directly mounted to the baseplate that also supports the complete structure through satellite bus mounting flexures.

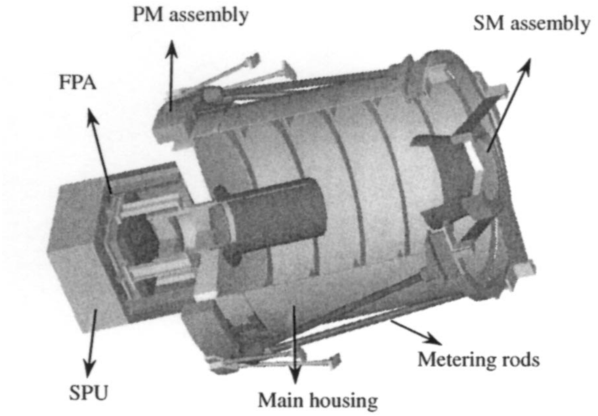

Figure 6 - Mechanical configuration of EOS

Both mirrors are solid ones made with Zerodur. Invar is used for metering rods, FPA supports and secondary mirror housing. All flexures are made with Stainless Steel. Aluminum is used for baseplate and secondary mirror ring and CFRP for main housing.

Static and dynamic analyses were performed for EOS such as self-weight deformation, frequency response, random vibration and shock analysis. The analysis result is summarized below.

- Mirror surface deformation due to gravity is within tolerance.
- Natural frequencies are about 150 and 200 Hz in lateral and vertical directions, respectively.
- No failure is expected from random vibration.
- No failure is expected from shock except for the primary mirror in vertical direction.

The optimization of primary mirror flexures is required to avoid its failure in vertical direction.

A preliminary thermal analysis was also performed for the complete EOS. The temperature distribution around EOS was analyzed for four different orientations of EOS. EOS was assumed sub-merged within the satellite bus structure while the entrance baffle is thermally coupled. The temperature distribution around EOS was also assumed based on past experience for four orientations. The analysis result is summarized below.

- Maximum temperature gradient is about 10 °C during imaging.
- Deformation of primary mirror surface due to thermal soak is out of tolerance.
- Modification of metering rod interfaces is required to compensate the variation of metering rod length.

The optimization of primary mirror flexures is required to minimize the thermal surface deformation. It is believed that the selection of optimum interface positions to Aluminum baseplate and secondary mirror ring can compensate the variation of metering rod length.

5.3. Signal processing electronics

Instead of packaged detectors, bare detector dies are used in FPA in order to minimize the optical field-of-view and to allow the bonding of detectors with high alignment precision and flatness. Each detector die has 8,192 active pixels of 7 μm pitch. Five dies are aligned and bonded on a common carrier that is patterned with signal tracks and alignment reference points. As an alternative approach, using a section of detector wafer is under consideration. This detector module is located within the FPA housing, which also houses the front-end electronics of clock drivers and pre-amplifiers. FPA also includes a thermo-electric cooler to maintain its temperature whose current flow is controlled by TPU.

Analog video signals from five detectors are processed and sampled within SPU. The sequencer logic programmed in a single FPGA provides all timing signals to read out detectors and to process their output signals. Each video signal is quantized into 10 bits and 8 most significant bits are multiplexed by the sequencer logic and transmitted to MMU at a speed of about 355 Mbps using an LVDS (low-voltage differential signal) interface.

5.4. Mass storage electronics

MMU consists of two fully redundant control modules and two independent storage modules. TS68EN360 and MPC860 are candidate processors for control modules. The control module is responsible for the overall management of the complete system in normal modes. An asynchronous communication link is used between control modules and the satellite bus to exchange command and telemetry data and system parameters. The control module is also responsible for the maintenance of storage modules. Its program memories are protected with hamming coding while the image data is protected with Reed-Solomon coding.

For each storage module, 256 64-Mbits industrial-grade SDRAM devices are used to give the total capacity of 16 Gbits. Each module consists of four sub-modules, each of which consists of four PCBs stacked on top of each other. A similar sub-module used for KAISTSAT-4 program of SaTReC is shown in Figure 7.

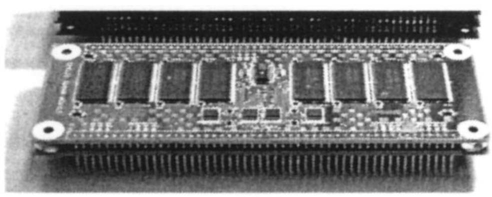

Figure 7 - 2-Gbits SDRAM sub-module (Courtesy of Samsung Electronics)

The control module performs a regular memory test to identify and isolate damaged memory devices. Figure 8 shows the organization of each storage module. The control module can isolate any damaged memory banks, sub-module packs or sub-modules, which gives multiple-level fault tolerance. In addition, this architecture allows easy expansion of storage capacity.

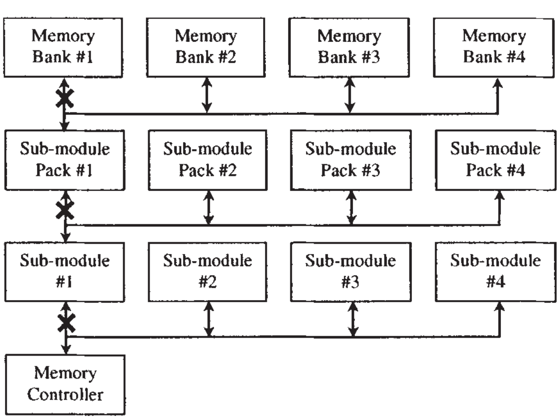

Figure 8 - Architecture of storage module for multiple-level fault tolerance

5.5. Future Plan for EM

More optimization and trade-off studies for EM are scheduled. Attention will be paid on the overall EOS opto-mechanical structure for its optimization and mass reduction and the optimization of primary mirror flexures to avoid any failure or large deformation of the mirror surface. A more in-depth thermal analysis is also planned.

According to the current schedule, the manufacturing of EM will be complete by March 02 and the AIT by May 02. Along the manufacturing phase, various experiments and tests are planned at component or assembly levels.

6. CONCLUSION

Micro- or small satellites have seen rapid growth over the last decade. Spurred by the advance of technologies and the need for more cost-effective missions, the growth will likely to continue for the next few years. In the field of earth observation, it is anticipated that these satellites will become a valuable tool for various applications and for technology development and demonstration.

It is hoped that the MAC system will demonstrate the value of small satellites and their imaging systems for cost-effective high-resolution earth observation. It is also hoped that this collaborative program will become a benchmark of genuine collaboration programs that give benefit to all organizations involved in such programs.

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