Development of a High-Performance Optical System for Small Satellites

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Abstract Funded by the Ministry of Commerce, Industry, and Energy of Korea, Satrec Initiative has initiated the development of the prototype model of a TMA-based electro-optical system as part of the national space research and development program. Its optical aperture diameter is 120 mm, the effective focal length is 462 mm, and its full field-of-view is 5.08 degrees. The dimension is about 600mm × 400mm × 400mm and its weight is less than 15 kg.
To demonstrate its performance and versatility, hyper-spectral imaging using a linear spectral filter was chosen as the application of the prototype. The spectral resolution will be less than 10 nm and the number of channels will be more than 40 in visible and near-infrared region.
In this paper, the progress made so far on the prototype development and the future plan will be presented.

1 Introduction

Satrec Initiative (SI) has continued the development of new technology for electro-optical sensor systems for several Earth observation missions using small satellites. Recently, the technology development efforts within SI have been focused on advanced optical and opto-mechanical systems to meet the increasing demand from

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scientific and remote sensing communities. Funded by the Ministry of Commerce, Industry, and Energy of Korea in 2005, SI has initiated the development of the prototype model of an advanced high-performance optical system, the TIS system as part of the national space research and development program.

The TIS system is designed to be versatile with a wide field-of-view, no obscuration, and no refractive element. Therefore, it can be used for various missions such as super-swath imaging, hyper-spectral imaging, infrared imaging, and aerial imaging. In addition, its compactness and light weight are ideal for small satellites.

The development of two prototype models is planned together with a field test for each model. The progress made so far on the 1st prototype development will be presented: optical design, analysis, and manufacturing; opto-mechanical design, analysis, and manufacturing; and demonstration of hyper-spectral imaging.

2 System Overview

The TIS system is based on an un-obscured three-mirror-anastigmat (TMA) telescope that consists of three mirrors. The optical design was simplified to use an on-axis spherical secondary mirror. The primary and tertiary mirrors are off-axis segmented aspheric mirrors. Its optical aperture is 120 mm, its effective focal length is 462 mm, and its full field-of-view is 5.08 degrees. It has a box-type structure with a dimension of 600mm $\times$ 400mm $\times$ 400mm and the weight is less than 15 kg.

The key features of the TIS system are listed in Table 1. As can be seen in Table 1, the TIS system is designed for dual applications of high-resolution panchromatic (PAN) imaging and hyper-spectral (HS) imaging. The ground sample distance (GSD) at 470 km altitude is 5 m for a PAN and 15 m for HS imaging channels. The spectral band range is from 450 to 890 nm and the spectral resolution is less than 10 nm for HS channels. The number of HS channels is more than 40.

Table 1 Key features of TIS 1st prototype model

Clear Aperture Size	120 mm	
Number of Imaging channels	PAN	1
	HS	≥ 40
GSD (m) @ 470 km	PAN	5 m
	HS	15 m
Swath width @ 470 km	≥ 40 km	
MTF (%)	PAN	≥ 10
	HS	≥ 20
Spectral Range	PAN	$500 \sim 700$ nm
	HS	$450 \sim 890$ nm
Spectral Resolution for H-ch	≤ 10 nm	
Dimension	600mm $\times$ 400mm $\times$ 400mm	
Weight	≤ 15 kg	

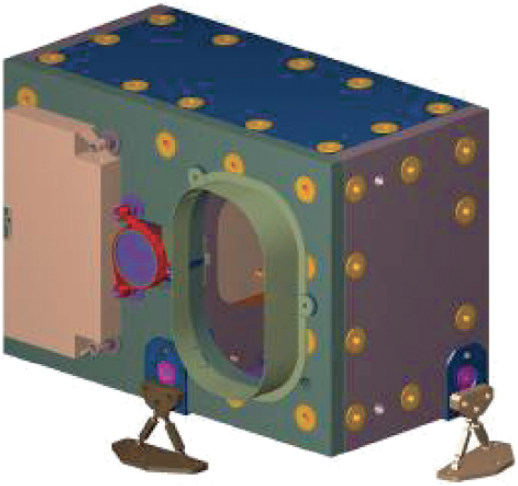


Fig. 1 Front view of 1st TIS Telescope

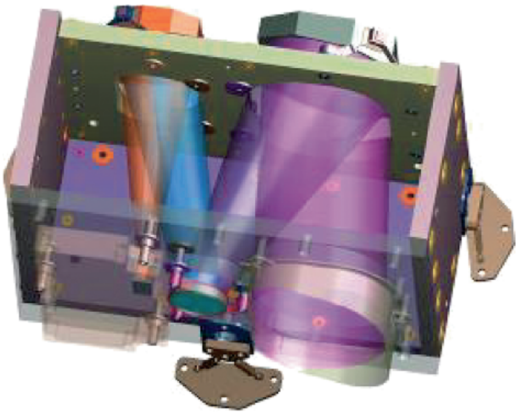


Fig. 2 Exploded view of 1st TIS Telescope

The box-type structure of the TIS system is based on honeycomb panels with composite face-sheets designed to minimize mass and to have enough stiffness. The reference planes for the optical surfaces are implemented with invar inserts through the honeycomb panels.

The spectrometer of the TIS system is implemented with a linear variable filter (LVF) on a two-dimensional detector array instead of conventional dispersive elements such as prism and grating. The spectral resolution is less than 10 nm, typically less than 1% of central wavelength over 450 $\sim$ 890 nm spectral range.

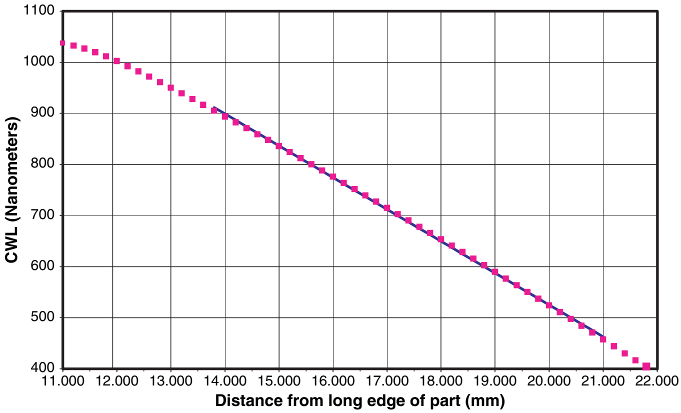


Fig. 3 Spectral range, dispersion and linearity of LVF

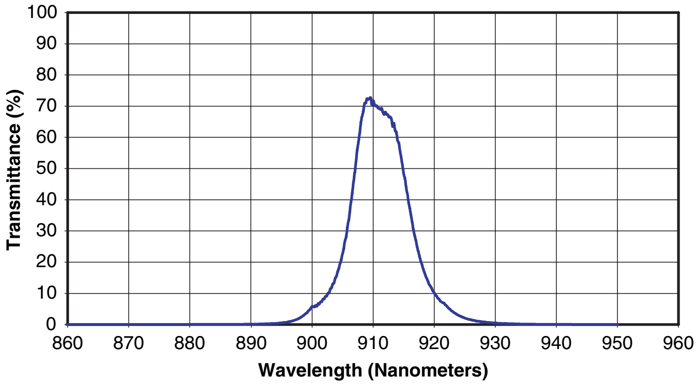


Fig. 4 Spectral resolution and transmittance of LVF at 910 nm

3 Development of Prototype Model

3.1 Optical Design and Analysis

The optical design of the TIS system has two advantages compared with conventional TMA designs: manufacturing and alignment. Using aspheric surfaces for an optical system usually gives high performance but, it will increase the manufacturing cost and needs a complex alignment process. To minimize the manufacturing cost and to make the alignment process simpler, the secondary mirror of the TIS system is an on-axis spherical mirror and the tertiary mirror has a small deviation from a spherical surface.

The primary mirror has a hyperbolic surface of conic constant of about −1.3 and the tertiary mirror has an oblate elliptical surface of conic constant of about 0.2.

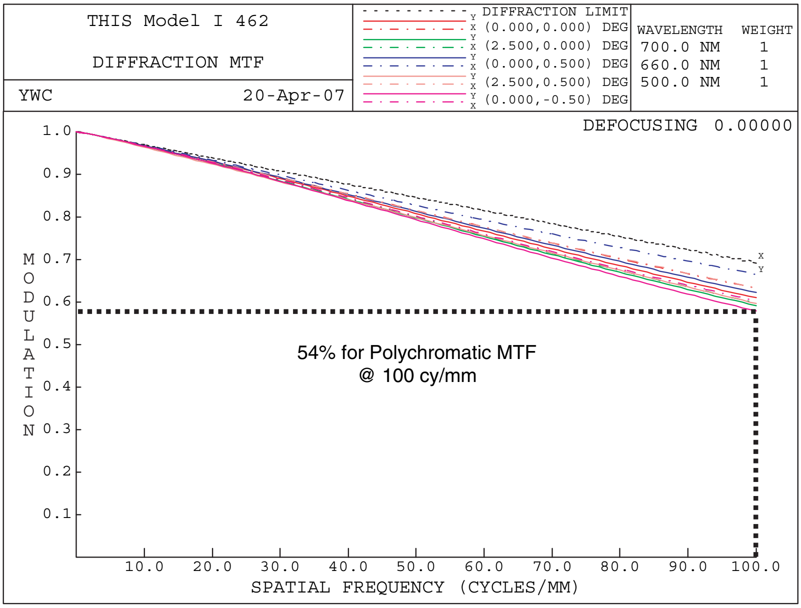


Fig. 5 MTF estimation for PAN band

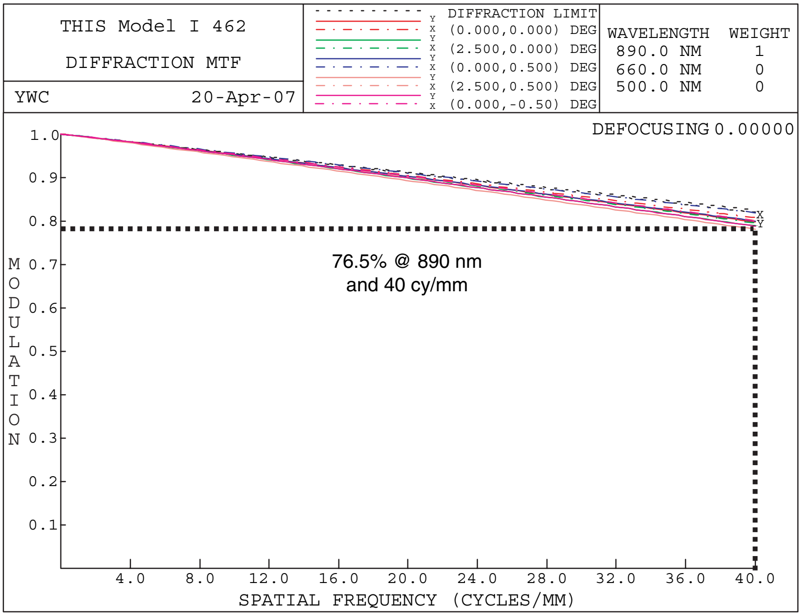


Fig. 6 MTF estimation for 890 nm

These two mirrors are manufactured to have a surface quality of λ/17 rms and the secondary mirror of λ/10 PV at λ of 632.8 nm.

The design MTF (modulation transfer function) is estimated to be more than 54% at 100 cycles per mm for the panchromatic band and is more than 76% at 40 cycles per mm for 890 nm. The design MTF at shorter wavelength is higher than that of 890 nm.

To predict the telescope performance, a tolerance analysis is performed in wavefront error (WFE) and MTF. The tolerance analysis includes manufacturing, assembly, and alignment errors. The parameters used for the analysis includes the surface quality of mirrors. The analysis shows a wavefront error of 0.149 λ at the corner of the image plane and the panchromatic MTF of 34% in across-track and 32% in along-track direction at 100 cycles per mm. If the detector MTF is assumed to be 45%, the TIS system will give MTF values of 15.3 and 14.4% in across and along-track directions, respectively.

3.2 Alignment of Optics

The alignment of the telescope started with the precision installation of the tertiary mirror (M3) with respect to the primary mirror (M1). From the tolerance analysis, the alignment result showed that the installation of M3 was successful within 100 μm for de-center and 10 arc-min for tilt.

The secondary mirror (M2) was aligned in two steps: coarse alignment and precision alignment. The coarse alignment of M2 was performed with respect to M1 using CMMs (coordinate measurement machines) and alignment telescopes. CMMs were used to correct the M2 de-center and de-space and alignment telescopes to correct the M2 tilt. It is estimated that the coarse alignment of M2 was successful within 50 μm for de-center and 5 arc-min for tilt.

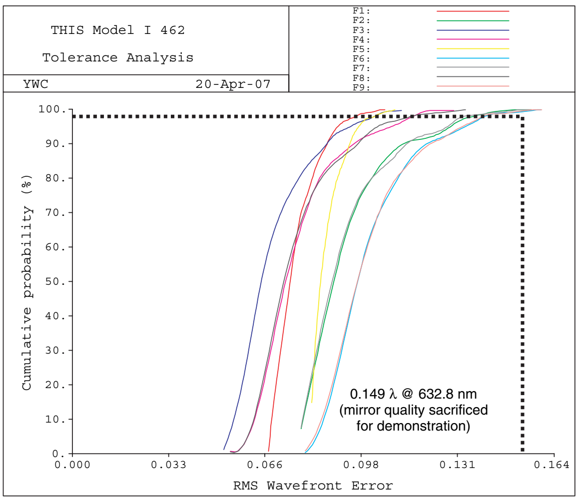


Fig. 7 WFE prediction for secondary mirror alignment

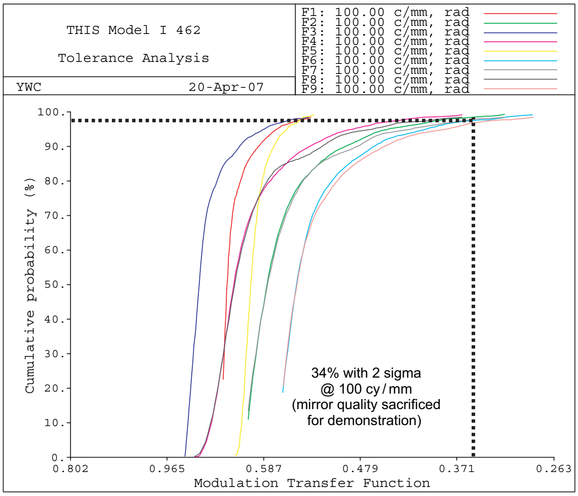


Fig. 8 MTF prediction for PAN in across-track direction

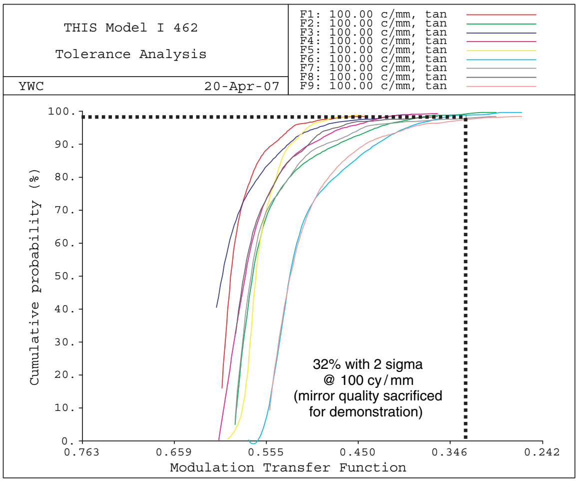


Fig. 9 MTF prediction for PAN in along-track direction

For the precision alignment of M2, a computer-aided alignment (CAA) based on the Zernike sensitivity was planned but it was not successful. It is believed that this was caused by the fact that the Zernike calculation perpendicular to the exit pupil was not correct because the image plane is slanted against the optical axis.

For the precision alignment of M2, the sensitivity of M2 movement was measured. The optimum position and tilt was estimated based on the measured sensitivity. To verify the alignment, a tolerance analysis on WFE and MTF was performed for a monochromatic band (632.8 nm).

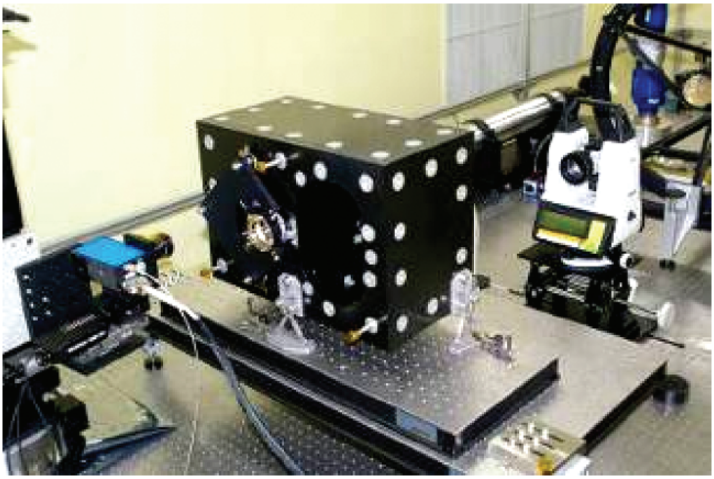
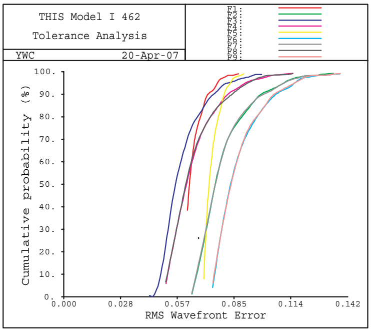
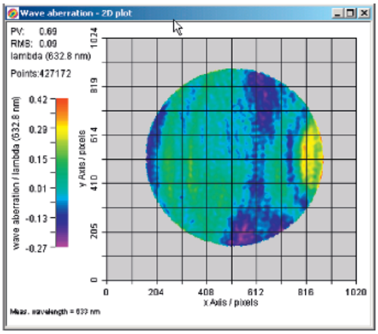


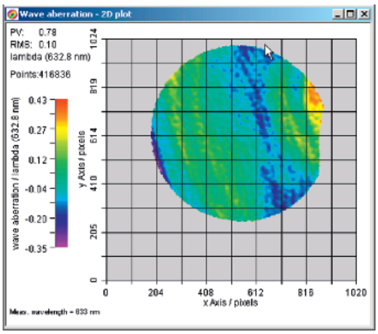
Fig. 10 M2 Alignment



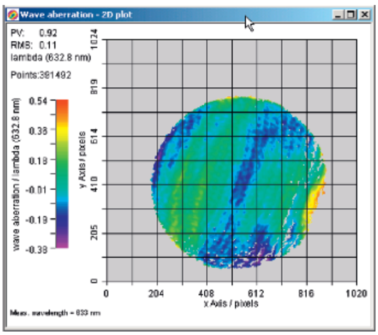
(a) Estimated WFE = 0.129λ rms



(b) Measured WFE = 0.09λ rms @ F(0,0)



(c) Measured WFE = 0.10λ rms @ F(1,0)



(d) Measured WFE = 0.11λ rms @ F(-1,0)

Fig. 11 Estimated and Measured WFE for M2 Alignmentf (**a**) Estimated WFE = 0.129 λ rms, (**b**) Measured WFE = 0.09 λ rms @ F(0,0), (**c**) Measured WFE = 0.10 λ rms @ F(1,0), (**d**) Measured WFE = 0.11 λ rms @ F(−1,0)

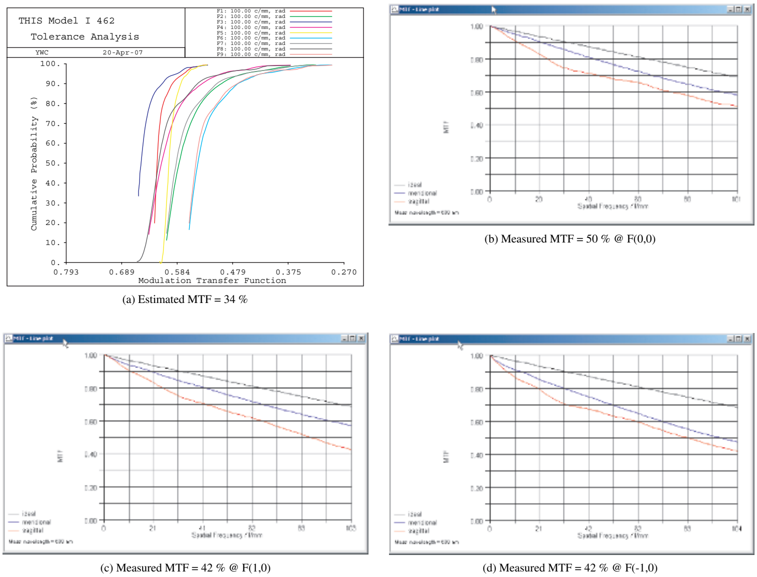


Fig. 12 Estimated and Measured MTF for the Alignment of M2(**a**) Estimated MTF = 34%, (**b**) Measured MTF = 50% @ F(0,0), (**c**) Measured MTF = 42% @ F(1,0), (**d**) Measured MTF = 42% @ F(−1,0)

3.3 Structure Verification

A random vibration test for the TIS structure model (SM) was performed before the optical alignment to investigate the structural stiffness and to obtain the notching profile. The first excitation was measured at 130 Hz from the interface flexure of the main structure. Others were measured at frequencies higher than 300 Hz from translational and local motions of the structure and at frequencies higher than 900 Hz for the motion of mirror assemblies.

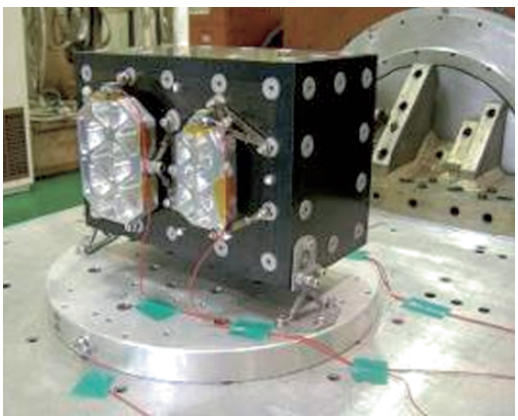


Fig. 13 Random vibration test of SM

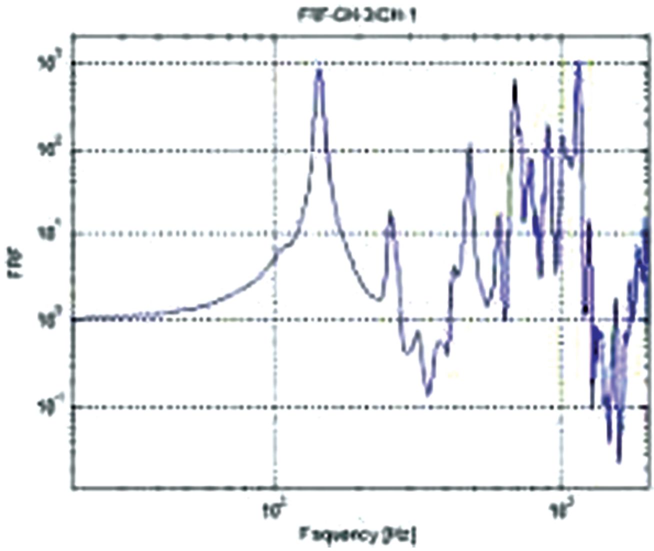


Fig. 14 M1 FRF in Y axis

3.4 Demonstration of Spectrometer

For the verification of the spectrometer of the TIS system, a commercial lens and a target simulator were used. Figure 15 shows the mages acquired in the channel 22 (551 nm), 30 (588 nm), 47 (665 nm), and 62 (734 nm).

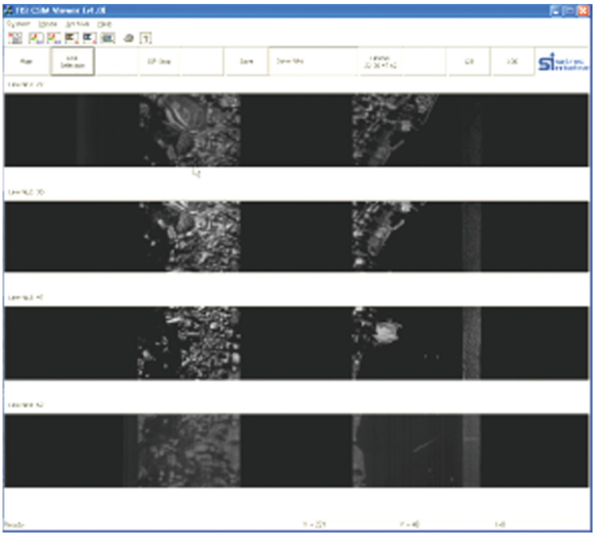


Fig. 15 Demonstration of Spectrometer performance in different channels

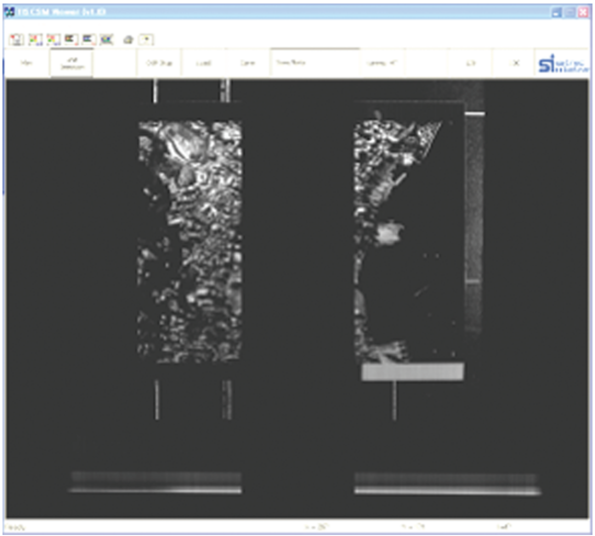


Fig. 16 Image captured in channel 47

4 Future Plan

With the completion of the optical alignment and test for the 1st prototype model, a random vibration test will be performed with actual mirrors in early May, 2007. The development of the 1st prototype model will be completed by the end of August, 2007 with the hyper-spectral imaging demonstration through a field test.

In parallel, the development of 2nd prototype model has been initiated. The 2nd model will have a bigger optical aperture of 150 mm and thus, the complete system will become larger and will give higher performance compared with the 1st model. The 2nd model will give 5 m GSD for one panchromatic and 10 m GSD for four multi-spectral bands at the design orbit of 685 km. The imaging swath width will be larger than 60 km at the design orbit. With the estimated system MTF values of 10% for the panchromatic band and 20% for multi-spectral bands, the 2nd model will produce high-resolution images of high quality.