

IMAGE SENSING AND PROCESSING OF BCCSAT-1 SATELLITE MISSIONS USING 4 MULTISPECTRAL CAMERAS

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Abstract

This paper will discuss the image sensing and processing of the BCCSAT-1. Every CubeSat needs a personalized space mission. In the case of BCCSAT-1, our primary mission is to improve Thailand's agricultural practices which largely contribute to the GDP and the stability of food supply of the country. Furthermore, this paper will provide a detailed explanation of the payload system which is designed to capture geographical images of the Earth using 4 CMOS cameras with 3 different filters to produce a multispectral image. By extracting each band from the multispectral image and processing it, we can generate an image showing the relative biomass. We are using two standardized vegetation indexes that allow us to estimate the relative biomass: Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge Index (NDRE). NDVI is a standardized vegetation index and often used for many applications. However, NDVI result images are usually oversaturated, as values in dense vegetation area -such as crop fields, rainforests, etc- are too high which makes it difficult to distinguish between healthy and unhealthy plants. As a complement, NDRE provides a higher dynamic range and deeper insight into dense vegetation area. A series of preliminary experiments are conducted using the BCCSAT-1 payload to verify that NDVI and NDRE provide useful insights into crops even in the densest vegetation area of Thailand.

Keywords: 1U cubeSat, multispectral camera, remote sensing, NDVI, NDRE

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Introduction

As advances in technology make payloads and instruments smaller, cheaper, and more efficiency, ideas of starting space-missions are now tangible for institutions, universities, and even high school. With the miniaturization of electronics, satellites emerged into smaller units while retaining its capability from conventional large satellites. CubeSat was first proposed in 1999 by Prof. Jordi Puig-Suari of California Polytechnic State University and Prof. Bob Twiggs of Stanford University. The standard design of the CubeSat is 10 by 10 by 10 cm with a mass not exceeding 1.33 kg (Munakata, 2009). It can also be designed as 2U (20×10×10cm), 3U (30×10×10cm), and other sizes depending on the satellite missions.

BCCSAT-1 is a high school student's CubeSat scheduled to launch into a sun-synchronized circular orbit at approximately 575 km in 2020 by a Russian rocket, Soyuz 2. The purpose of this CubeSat project is to educate Bangkok Christian College high school students in the space engineering field using real-world experiences, especially project-based learning. These students learn the real-world experiences from hands-on-training project, satellite designing, experiments and result findings, project risk management, team working, and effective use of time and budget.

Agriculture has been the backbone of Thai's society. Thailand's economy has significantly been based on the agriculture activities, which employs approximately 35 percent or one-third of 70 million population in the country and accounts for 25% of total exports by value (Food and Agriculture Organization of the United Nation, 2018).

As societies and technologies grows, people have been coming up with ways to improve agriculture. In a recent development, precision agricultural practices have significantly improved the productivity and profitability of crops. Precision agricultural practices provide farmers with valuable information, allowing for more precise and wise management of the environment and inputs that affect the crops. (Singh *et al.*, 2015) One of the precision crop management is the

nitrogen management which is essential to growth and yield of crops. In which, image sensing of crop canopy spectral reflectance using NDVI and other indices can be used to measure the biomass. These indices typically use multiple wavelengths of radiation that plants reflect to calculate and analyse biological conditions of vegetation (Dawson *et al.*, 2003).

Chlorophyll pigments in plants absorb red light (650 nm) and blue light (450 nm). On the other hand, the red edge (670 nm) and NIR (750 nm) are reflected (Figure 1). Furthermore, there is an increase in red absorption and red edge and NIR reflection whenever the amount of chlorophyll and nitrogen increases in the crop. In contrast, red absorption and red edge and NIR reflection decreases, whenever the amount of chlorophyll and nitrogen decreases. As a result, these can be used as a sensitive indicator of vegetation stress and health (Lupidi and Masini 2015).

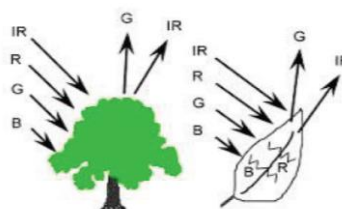


Figure 1. Chlorophyll pigments absorption process (Lupidi and Masini, 2015)

Mission Overview

The main mission of BCCSAT-1 is to capture geographical images of the Earth using four cameras from 5 different ranges of wavelength along the electromagnetic spectrum. By capturing four images with multiple ranges of wavelength simultaneously, we can create a multispectral image which can later be used to create indices such as NDVI and NDRE. Unlike drones and aircraft, the mission aims to provide information for precision agriculture

Table 1. Comparison of Commercial Cameras

Camera Module	Specification				Typical Power Consumption (W)	Price (£)
	Spectral Sensitivity	Array size	Spatial Resolution	Mass		
SCS Gecko Imager	RGB	2.2 MP	39 m	480 g	2.7	23,000
Argus 1,000 IR	1,000-1,700nm	N/A	6 nm	280 g	1.5	42,000
NanoCam C1U	400-750 nm	3 MP	Varies ¹	169 g	0.8	N/A ²
CAM1U	RGB	5 MP	600 m	50 g	0.24	N/A ²
XCAM C3D	RGB or B&W	1.3 MP	360 m	85 g	0.845	N/A ²
OV5642	RGBNIR	5 MP	Varies ¹	20 g	1	24.21 ³

- Depends on the lens configuration

- Requires Enquiry

- Exchange Rate: 1 USD = 0.810 GBP

on a large scale and over a long period using minimal budget.

Camera Modules

To perform the main mission, we have considered many commercial off the shelf cameras and compared it with the specification which the BCCSAT-1 required. The comparison is shown in Table 1.

Taking everything into consideration, the BCCSAT-1 team have concluded that the OV5642 capability met the criteria to perform our mission successfully. Remarkable capabilities of the OV5642 are high resolution, low power consumption, modularity, lightweight, and broad spectral range. Many of the capabilities beat its competition despite its low price.

Filters

The Landsat Program provides the longest continuous space-based record of Earth's land (National Center for Atmospheric Research Staff, 2013). Landsat satellites have been very successful in providing precise and essential information for customers. Thus, we chose Landsat 8 ranges of wavelength as a reference for our wavelength and filter selection, shown in Table 2.

Filters should be chosen according to the limitation of the camera module and the mission of the satellite. In the BCCSAT-1, the primary range along the electromagnetic spectrum that the camera support is red, green, blue, red edge, and NIR. The main missions - image sensing and processing using NDVI and

Table 2. Band designations for Landsat 8 satellite

Bands	Wavelength (micrometers)
Band 1 - Coastal aerosol	0.43-0.45
Band 2 - Blue	0.45-0.51
Band 3 - Green	0.53-0.59
Band 4 - Red	0.64-0.67
Band 5 - Near Infrared (NIR)	0.85-0.88
Band 6 - SWIR 1	1.57-1.65
Band 7 - SWIR 2	2.11-2.29
Band 8 - Panchromatic	0.50-0.68
Band 9 - Cirrus	1.36-1.38
Band 10 - Thermal Infrared (TIRS) 1	10.6-11.19
Band 11 - Thermal Infrared (TIRS) 2	11.50-12.51

(Obtained from USGS)

Table 3. Filters list

No.	Chosen Bands	Wavelength (nm)
1	Blue, Green, NIR	475/550/85
2	Green, Red	550/650
3	Red Edge	725
4	None (Natural)	RGB

NDRE - requires red, NIR, and red edge. However, due to the limitation of our CubeSat, we can only mount a total of 4 maximum filter. To configure the filters to include more than four bands of wavelengths, we can use a dual bandpass and triple bandpass filter to allow for more than one band of wavelength per camera as shown in Table 3 (Filter No.1 and 2).

Furthermore, to be able to determine the location of the image without an active The Attitude Determination and Control System (ADCS), we included a standard camera with no filters (NIR cut only) to allow us to take a natural colour picture. Finally, due to the

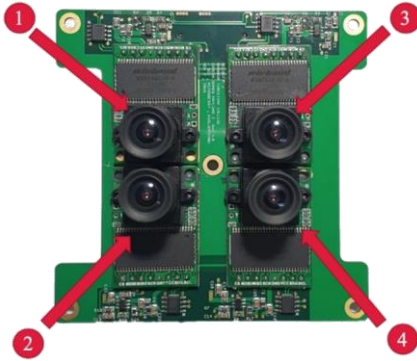


Figure 2. Camera arrangement on the payload board

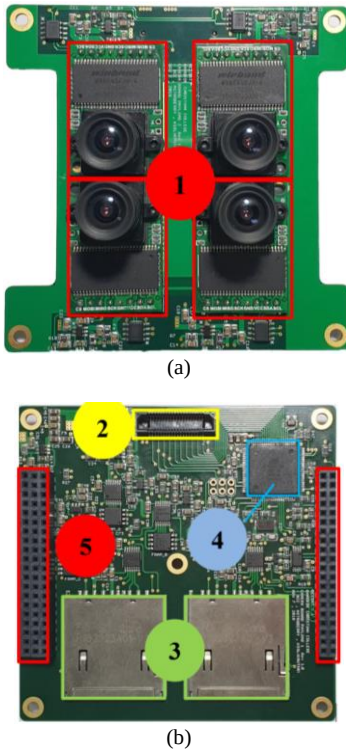


Figure 3. (a) Payload Board - (1) Four OV5642 (b) CDH Board - (2) CDH-Payload pin (3) SD Cards Slot (4) Atmega2560 (5) Standard Pin

difference in positions of our cameras, we allowed green light to pass into our camera in 2 of our filters. The included green band in the

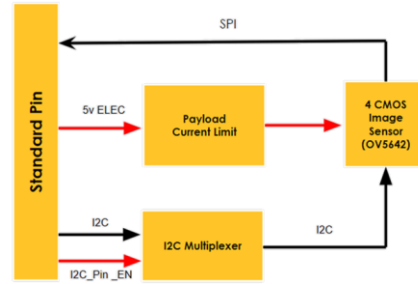


Figure 4. Payload's block diagram

multispectral image will help us align all the images together by using it as a reference.

The Payload Board and CDH Board

Combining all the components in circuit design, the payload board is engineered to accommodate the OV5642 modules and the communication between the Payload board (Figure 3(a)), and the Command and Data Handling (CDH) board (Figure 3(b)).

The main components in the payload board are the four camera modules (1). The main components in the CDH board are the CDH-Payload pin (2) that allow direct communication of the CDH Board to the Payload Board, the SD Cards Slot (3) the primary storage for our system, the main MCU [Atmega2560] (4) for command and data handling of the whole system, and Standard Pin (5) that connects every other subsystem. Direct communications between the payload board and the CDH board are as shown in Figure 4.

The Payload subsystem is controlled by the CDH MCU through the I2C bus. The I2C multiplexer enables the communication between the CDH MCU and I2C bus. Each camera modules are powered by a 5v bus which is protected by a Payload Current Limiter. Pictures and data are sent from the cameras through the SPI bus.

Image Processing

The OV5642 camera module is a CMOS sensor-based camera. When a picture is taken, each type of sensor (R, G, B) (Figure 5) only

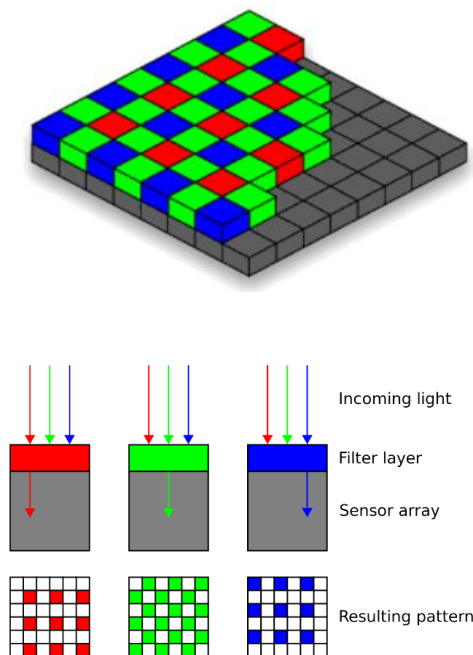


Figure 5. Bayer mosaic of colour image (Zapryanov and Nikolova, 2005)

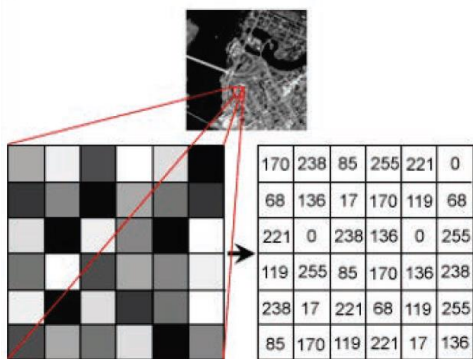


Figure 6. Digital image (Lupidi and Masini, 2015)

accepts its corresponding specific range of wavelength. Each pixel records values, which corresponds to the measured average radiance shown in Figure 6. Thus, the result digital image contains three layers of values matrix, each assign to their corresponding range of wavelength. We can extract these layers from

the digital image and processed it with vegetation index. Indices like NDVI and NDRE are mathematical formula derives to output a numeric result in which we can analyse.

Normalized Difference Vegetation Index (NDVI)

As healthy green vegetation absorbs mostly the red wavelength due to the presence of leaf pigments (National Aeronautics and Space Administration, 2010). NDVI uses the ratio of NIR to red reflectance to analyse the remote sensing data to tell whether the object or area being observed contains healthy vegetation or not. NDVI can be calculated by

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

where *NIR* is visible near-infrared reflectance with a wavelength between 750 and 1,300 nm, and *Red* is visible red reflectance with a wavelength between 600 and 700 nm.

Calculations of NDVI for a given pixel will result in a number between -1 to +1, where positive values usually indicate dense vegetation (with denser vegetation closer to 1) and negative or near zero indicate non-vegetation (bare soil closer to 0; body of water, soil with a lot of moisture, and buildings in the negative range) (Pettorelli, 2013).

Problem with NDVI

NDVI is an excellent estimation of biomass and a great general indicator of vegetative health and known as a widely used algorithm. However, it is not accurate for all areas and stages of crop growth (Yengoh *et al.*, 2015). With the fact that ecosystem tend to modify their photosynthetic capacity in relation to available resources - changes in leaf area, foliar chlorophyll content, and species composition (Danson and Curran 1993) - and that NDVI is reported to has a nonlinear correlation with the Leaf Area Index (LAI) (Myneni *et al.* 1995; Huete *et al.* 2002). NDVI is usually oversaturated in some cases involving strong chlorophyll absorption band. Furthermore, differences in canopy level parameter, such as height, size, and the number

of trees, and the increasing of LAI approach saturation asymptotically to the vegetation index (Pettorelli, 2013).

Normalized Difference Red-Edge Index (NDRE)

Although there are problems posed by NDVI, we can use NDRE to compensate for its flaws. NDRE uses the ratio of NIR and red edge band. Red edge spectral region is the transition between the red and the near-infrared reflectance. It is more sensitive to moderate to high chlorophyll content compared to the visible red band that cannot penetrate very far past leaf layers.

Combining with the near-infrared, NDRE provides a better insight into later growth stages crop and observation of lower levels of the canopy since red edge is more translucent to leaves. Not only that, it is also less prone to saturation in dense vegetation. To sum up, NDRE improves sensitivity to differences in chlorophyll content, leaf, and canopy structure. Hence, it provides a better measurement of variability. NDRE can be calculated by (Lupidi and Masini, 2015)

$$NDRE = \frac{NIR - Red\ edge}{NIR + Red\ edge} \quad (2)$$

where *NIR* is visible near-infrared reflectance with a wavelength between 750 and 1,300 nm, and *Red edge* is visible red reflectance with wavelength between 690 and 730 nm.

Experiment

Two major experiments were conducted to validate our payload's functionality. Experiment 1 was designed to verify the processing for both NDVI and NDRE. Experiment 2's objective was to validate the four cameras function under extreme simulated space conditions: Thermal cycle test, and Vacuum thermal cycle test.

Experiment 1: Payload Function and Image Processing Validation

To ensure that selected filters (Natural band, Triple band [green, blue, NIR], and Red edge band) will provide both the NDVI and the

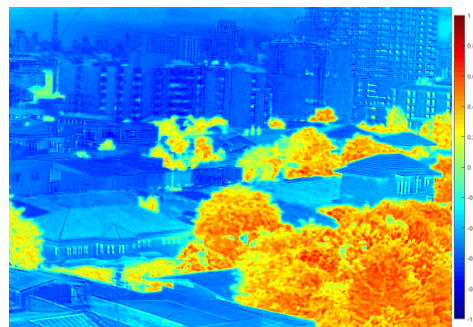
NDRE analysis, we brought the Bccsat-1's model to the roof of a moderate height building to perform an experiment on the payload.

NDVI results

The multispectral images captured on the roof is then imported into MATLAB to extract each layer and then analyse using the NDVI and NDRE formula to provide the NDVI and NDRE result. As shown in Figure 7, the picture before image processing (Figure 7(a)) compared to after image processing (Figure 7(b)) clearly isolates vegetation from non-vegetation. Further shown, healthier vegetations have NDVI value closer to +1, which can be seen in red and orange. On the other hand, unhealthy ones will be shown in yellow and green. Lastly, the non-vegetation such as infrastructures and houses are in blue with NDVI value near -1.



(a)



(b)

Figure 7. (a) Image before NDVI processing (b) Image after NDVI processing

NDRE results

The Result, as can be seen in Figure 8(a) in the image, is oversaturated and it is tough to identify the differences among high NDVI values. As healthy vegetation turns out to have an average value between 0.8-1. On the other hand, NDRE in the Figure 8(b) has lowered the saturation levels hence it modified those saturated red pixels to vegetation with greater details.

Experiment 2: Space Environmental Testing

Thermal cycle test

To ensure that our Cubesat is able to endure the harsh conditions that is space, we thermal tested the CubeSat. The selected thermal profile was chosen to have a realistic temperature profile, the profile had a maximum of 55 degrees Celsius and a minimum of -10 degrees Celsius. The profile

we used is provided in Figure 9(b). In the preparation phase we placed the CubeSat in the test chamber and lowered the temperature to -10 degrees Celsius for 10 min. After the preparation phase, we started the thermal cycle. The thermal cycle starts when we raised the temperature to around 55 degrees for 60 min, afterward we decrease it to -10 degrees for 35 min and the cycle repeats. This profile is specifically used to simulate the CubeSat orbital environment (60 min in the sun and 35 min in the umbra). We then validated our system by sending commands through the wiring hole provided beside the chamber (Figure 9(a)) to the CDH board which in turn communicate with the Payload Board to take a picture with every camera when the temperature reach it peaks (both -10 and 55 degree Celsius).

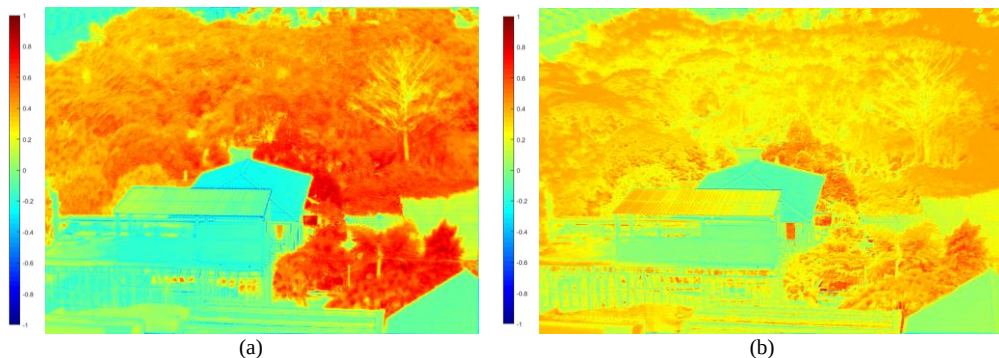


Figure 8. Comparison between NDVI and NRDE (a) NDVI (b) NDRE

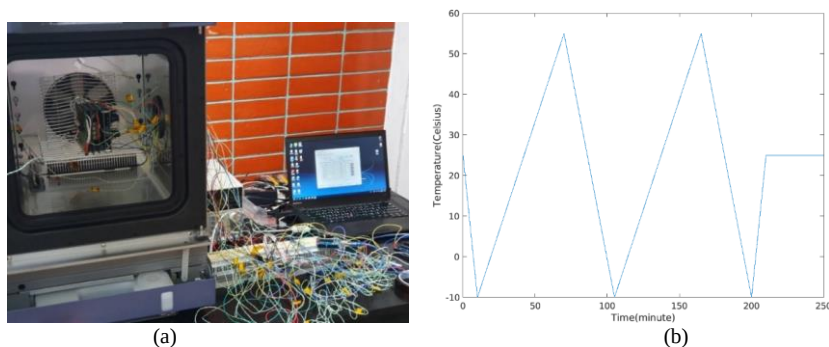


Figure 9. (a) Experiment Set up (b) Thermal cycle temperature profile

Vacuum Thermal Cycle

Thermal vacuum testing simulates the worst possible temperatures that the CubeSat might encounter. The experimental setup is shown in Figure 10. Once we start, the chamber will undergo changes to reduce the pressure to extreme vacuum (Pressure $<1 \times 10^{-10}$ pascal). The chamber then starts to cool down to a temperature of -30 Degrees Celsius. Then heats up to around 55 Degrees Celsius with a hang time to perform the functional test for

2 h. The functional test is performed every hang time (highest and lowest temperature). This ensures that under normal circumstances, the payload can take multispectral images while in orbit. We also use 11 thermocouples attached to our CubeSat to determine the most accurate temperature. As the pictures in Figures 12(a), 12(b), 12(c), and 12(d) shows, our CubeSat can take pictures during the worst possible condition our CubeSat might encounter.

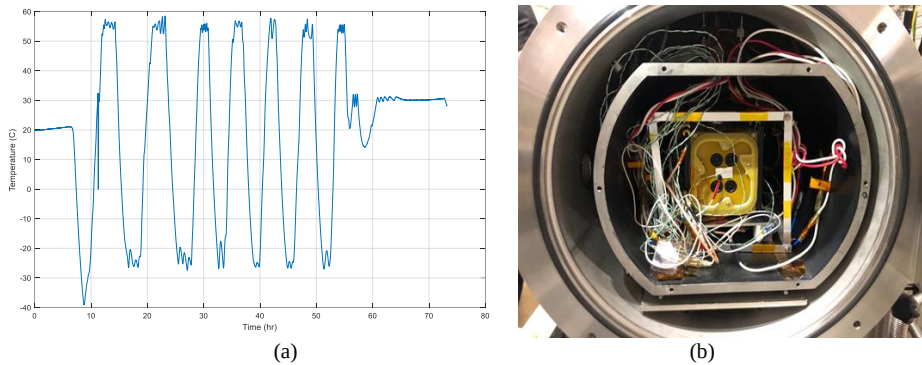


Figure 10. (a) Thermal cycle temperature profile (b) BCCSAT-1 Placement in the Chamber

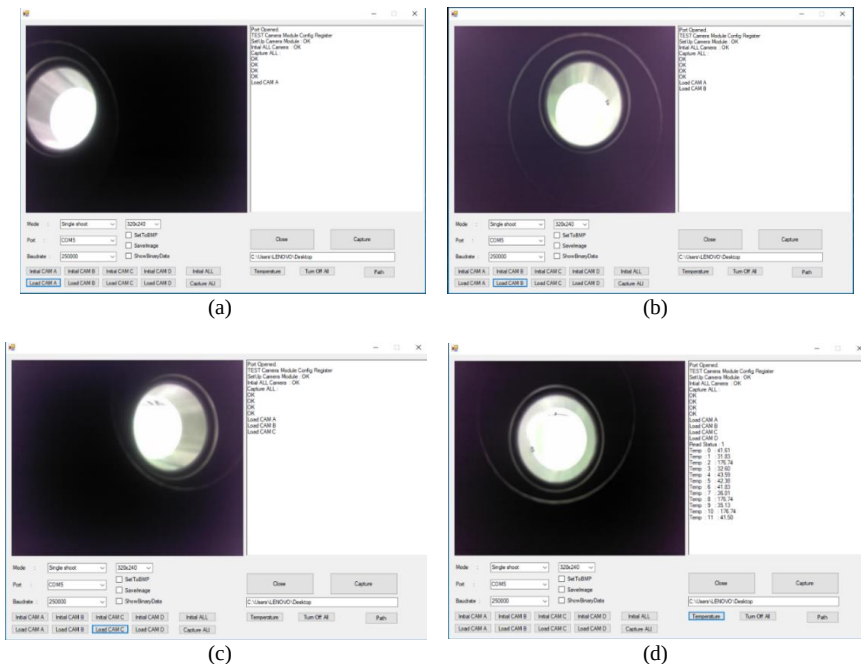


Figure 11. 4 cameras capturing images at -25°C

Result

The results show that the CubeSat could take pictures under both the extreme conditions and the likely condition the CubeSat would face while in orbit. There were no errors or interference during the period where the CubeSat was tested. This ensures the functionality of the 4 cameras module in the simulated space conditions.

Conclusions

In the limited space of our CubeSat we can only mount 4 cameras on the payload board. With the advantage of multiple band pass, we are able to capture 5 channels of wavelength - Red (650 nm), Green (550 nm), Blue (475 nm), Nir (85 nm), Red Edge (725 nm) - in the multispectral image using only 3 CMOS cameras. As there is no ADCS-System in our CubeSat, we also include one additional CMOS camera without filter that help identify the location of image taken.

As NDVI results are empirically oversaturated in dense vegetation area because the spectral coverage of chosen Red band at 650nm is insensitive to moderate to high chlorophyll concentrations. But with the shifts in the Red edge band that is reported to be related to changes in chlorophyll concentrations; NDRE is able to increase the variability of data by improving sensitivity to differences in chlorophyll content, leaf, and canopy structure. This is proven in the experiments mentioned. Finally, we have verified the functionality of our camera modules through multiple simulated space environment tests.

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