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The HYPSO RGB cameras

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Abstract

The HYPSO-1 (HYPerspetral Smallsat for Ocean observation 1) 6U CubeSat, which was launched in January 2022, houses two imaging payloads which are mostly made of cost-effective Commercial-off-the-Shelf (COTS) components. The satellite includes a COTS onboard processing unit (OPU) with field programmable gate array (FPGA) for camera control and data processing. The main imaging payload is a push-broom hyperspectral camera designed for ocean color remote sensing, and the secondary payload is a snapshot Red-Green-Blue (RGB) camera to aid in georeferencing of the hyperspectral data. The images from the HYPSO-1 RGB camera suffer from optical issues that heavily degrade image quality due to errors made during the instrument design and testing phases. The aim of this work is to redesign the HYPSO-1 RGB camera for the successor CubeSat HYPSO-2 to enable the use of RGB-hyperspectral super-resolution methods.

We present the cause of the image quality issues of the HYPSO-1 RGB camera and the process from design to application of a high spatial resolution RGB snapshot camera for HYPSO-2. More specifically, this work includes 1) Optical design of the RGB camera with a trade-off between motion blur and light throughput 2) imaging scheduling methods to align the coverage of the RGB and hyperspectral cameras for HYPSO-2, while considering their differing instantaneous field of views, and 3) Orbital images from HYPSO-2 after its launch in August 2024.

The optical redesign of the RGB camera achieves 28 m Ground Sampling Distance (GSD) at nadir from a 590 km altitude, which is 2.5 times smaller than the GSD of the hyperspectral camera. The performance of the optical redesign is verified by ground tests and on-orbit imagery.
Keywords: Cubesat, Commercial-off-the-Shelf, Paylod design, Hyperspectral, Superresolution.

Acronyms/Abbreviations

Hyperspectral Smallsats for Ocean Observation (HYPSO)
Norwegian University of Science and Technology (NTNU)
Red-Green-Blue (RGB)
HyperSpectral (HS)
Hyperspectral imager (HSI)
Commercial Off-the-Shelf (COTS)
Flight Model (FM)
Ground Sampling Distance (GSD)
Application Programming Interface (API)
Launch and Early Operation Phase (LEOP)

1. Introduction

Large earth observation satellites like Landsat and the Copernicus Sentinels feature a panchromatic sensor to enable a post-processing technique called *panchromatic sharpening*, that improves the visual fidelity of their multispectral images. Analogously, the RGB camera for the 6U CubeSat HYPSO-2 aims to improve the visual quality of its hyperspectral images. HYPSO-2 was launched into a 590 km sun-synchronous orbit in August 2024, two and a half years after its predecessor HYPSO-1 [1, 2]. HYPSO-2 contains the same push-broom hyperspectral instrument as the HYPSO-1, and uses upgraded communication interfaces. It can capture and downlink about 10 times as much hyperspectral data compared to HYPSO-1. HYPSO-1's RGB camera was intended to aid in georeferencing the hyperspectral instrument's data, but suffers from three optical issues, making it unusable for its intended application. The root causes of these issues were determined to be a lack of definition of responsibilities and a lack of proper testing procedures.

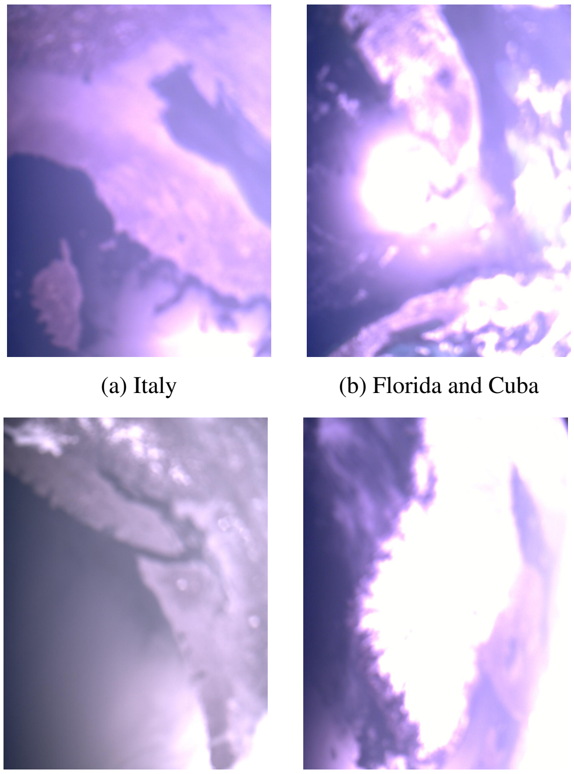
This paper's introduction continues with presenting the HYPSO-1 RGB camera and its optical issues, followed by the design method and additional considerations for the HYPSO-2 RGB camera. The results section presents the process of deciding on the new components for the HYPSO-2 RGB camera. The design choices are verified by in-orbit imagery from HYPSO-2. The last section concludes the paper.

1.1 The HYPSO-1 RGB camera

The HYPSO-1 RGB camera mostly consists of COTS components that can be divided into three parts: 1) the camera module with a focal plane array image sensor, 2) the objective lens, and 3) the mechanical housing and lens mount. The camera module is an iDS imaging UI-1252LE [3]. The objective lens is an Edmund Optics fixed focal length lens #86-591 [4]. The mechanical housing consists of a back-plate part, which was machined in-house, and a C-mount part, which was obtained from iDS imaging. See Figure 1 for an image of the assembled RGB camera before it is integrated into the greater payload system. The camera module has a USB 2.0 interface to the payload processor and is controlled using custom software that uses an API from the camera module manufacturer iDS imaging.

Fig. 1. Image of the HYPSO-1 RGB camera.

Figure 2 shows representative examples of the kinds of images that the RGB camera on HYPSO-1 takes. The three issues of the HYPSO-1 RGB camera are 1)the lens is not focused, 2) the images are discolored, and 3), the lens is too 'fast', meaning the fixed aperture of the lens was chosen to be too wide open. The defocus is likely due to insufficient mechanical support, causing the lens to shift in position during integration or launch. In addition, a fast lens with a wide aperture has a smaller depth of field compared to the same lens with a narrower aperture, which makes focusing more difficult. The reason for the discoloration was later found via ground testing to be due to the lack of an optical bandpass filter to limit the IR and UV light entering the front lens. Each image in Figure 2 has been captured with 40 µs exposure time. This is close to the minimum possible exposure time of 20 µs that the image sensor supports. The sensor response is no longer linear at these exposure times, and there is little difference between 20 µs and 40 µs. It is not possible to reduce the exposure time further so that bright targets such as ice and clouds are not overexposed, and still reveal structure in the Norwegian landscape. This issue was due to the choice of aperture which is too large compared to the light environment from low-earth orbit and the sensitivity of the camera module.



(a) Italy (b) Florida and Cuba

(c) USA/Canada west coast (d) Snow-covered Norway

Fig. 2. Example RGB images from HYPSO-1. The images are unfocused and discolored. Each image was acquired at 40 µs exposure time.

1.2 Impact for the mission and science

Several proper design and test procedures could have uncovered these issues and would have enabled us to solve the issues before launch. Proper procedures include testing of the camera in relevant light conditions or proper checkout of the FM after final assembly. The attitude telemetry from HYPSO-1 ADCS ended up being accurate enough for rough georeferencing. The loss of the RGB camera on HYPSO-1 thus did not lead to problems in georeferencing the hyperspectral data.

1.3 Redesign for HYPSO-2

This section presents considerations and methodologies used in the redesign of the RGB camera for HYPSO-2, to avoid the problems that are experienced with the HYPSO-1 RGB camera.

1.3.1 Goal: Superresolution

Without the need for coarse georeferencing, there is no need for a wide-angle snapshot camera. Thus, a new purpose was defined in terms of enabling superresolution

Table 1. Specifications of the HYPSO-1 RGB camera.

Property	Value
Camera module	iDS UI-1252LE [3]
Image sensor	EV76C570ACT
Pixel size	4.5 µm
Sensor size	7.2 by 5.4 mm
Pixel count	1600 by 1200 px
Exposure time range	0.02 - 10000 ms
Lens	Edmund Optics #86-591 [4]
Focal length	6 mm
Aperture	F/1.4
Nadir GSD @590 km	442 m
Field of view	62° by 48°
Nadir Swath @590 km	ca. 700 by 500 km

methods that enhance the hyperspectral data. This imposes a new spatial resolution requirement on the RGB camera. The redesigned RGB camera shall have a better spatial resolution than the hyperspectral camera to super-resolve the hyperspectral data. The variables of the components influencing spatial resolution are pixel size, focal length, and exposure time. The GSD of a focal plane array sensor as a function of focal length f, pixel size s, and when pointing nadir at an altitude h is approximately

$$\text{GSD} \approx h\frac{s}{f}. \tag{1}$$

For the HYPSO-2 HSI with $s = 5.86$ µm and $f = 50$ mm, the across-track GSD is 69.1 m. The requirement for the RGB camera ground sampling distance is to at least the HSI GSD or better. The changes to be made to the HYPSO-1 RGB camera design to fulfill this requirement can be achieved by using a longer lens with a larger focal length (increasing f), a new image sensor with a denser pixel array (decreasing s), or both.

1.3.2 Camera module

An overall shorter timeline and sparser resource allocation for the successor satellite HYPSO-2 constrains the redesign of the RGB camera for HYPSO-2 in terms of mechanical, electrical and data interface. The optimum solution would be to find a lens and camera module combination that achieves 69.1m GSD or better with the same mechanical form factor, the same electrical interface, and the same software API. The same API constraint implies looking for possible camera modules from the same company. The same mechanical form factor narrows down the set even more. The optical form factor constraint is using C-mount lenses. The electrical interface constraint is the use of USB 2.0.

The motion blur caused by a finite exposure time can degrade the effective spatial resolution to be unusable for superresolution. This imposes requirements on the pointing stability as a function of 1) supported exposure time range of the image sensor, 2) the speed of the lens (aperture), and 3) the desired image brightness. In this work, we have disregarded the pointing stabilit aspects and consider static pointing with respect to a local orbit following frame (the Local-Vertical Local-Horizon (LVLH) frame), because that was the most used pointing mode on HYPSO-1 for hyperspectral imaging. Assuming static pointing with respect to the LVLH frame, the distance d that a pixel travels on ground during image exposure caused by the satellite's orbital speed v is

$$\text{d} = ve, \tag{2}$$

where e is the exposure time. The orbital speed of a satellite in a circular orbit of altitude 590 km is ≈ 7.56 km/s. For this design, we consider a displacement during exposure that is less than the GSD of the sensor to be acceptable.

1.3.3 Focal length, field of view, and swath width

For a given camera module with a pixel size s, the focal length must be such that Equation (1) is less than the GSD requirement. Lenses with fixed focal length and fixed aperture are preferred, because variable focal length and variable aperture lenses contain unwanted mechanical complexity. The mechanical complexity will make preparing the lens for launch more difficult, and any lubrication may outgas and contaminate the optical components. Typical COTS C-mount focal lengths are 16 mm, 25 mm, 35 mm, 50 mm, and 100 mm.

Given a choice of sensor and lens, their sensor size l and focal length f determine the field of view and swath width at a given height. The camera field of view α is approximately

$$\alpha \approx 2h\,\tan^{-1}\frac{l}{2f}. \tag{3}$$

For a small field of view and while looking nadir, the swath width w of a camera at altitude h is approximately

$$w \approx h\frac{l}{f}. \tag{4}$$

For different choices of focal length, the swath width may be larger or smaller than the swath width of the hyperspectral camera. It is desirable to design the RGB camera with a larger swath width than the hyperspectral camera to maximize the parts of hyperspectral data that can be super-resolved. Given the most common imaging mode of HYPSO-1, the effective HSI sensor height is 6.4 mm. Using Equations (3) and (4) leads to a field of view of about 7.3 degrees and a swath width of about 75.5 km for the hyperspectral cameraat altitude 590 km.

Table 2. GSD and swath width for two different focal lengths for the candidate focal plane arrays from Table 3.

	f = 25 mm		f = 35 mm		f = 50 mm	
Sensor	**GSD**	**Swath**	**GSD**	**Swath**	**GSD**	**Swath**
EV76C560	125 m	160 x 128 km	89 m	114 x 91 km	62 m	80 x 64 km
MT9P006	52 m	133 x 100 km	37 m	95 x 71 km	26 m	66 x 50 km
MT9J003	39 m	151 x 108 km	**28 m**	**108 x 77 km**	20 m	76 x 54 km

1.3.4 Aperture

To avoid the saturation issue of the HYPSO-1 RGB camera, the aperture needs to be chosen such that the nominal exposure time for optimally exposed images is large enough to fall well within the possible exposure time range of the sensor. The nominal exposure time must not be too large to generate excessive motion blur, or too small to fall near the lower, non-linear exposure time region. By experiment, it was determined that the HPSO-1 RGB sensor becomes linear at an exposure time of around 100 µs, which is a factor of 5 above the lower limit. The aperture is measured in f-number. The f-number of COTS lenses varies among a set of discrete values, spaced in such a way that the next value corresponds to a doubling of light energy passing through the lens. Typical COTS f-numbers are 1.4, 1.8, 2.8, 4, 5.6, 8, and 11.

To determine a good f-number for the HYPSO-2 RGB camera, an empirical method is chosen. Different exposures of images of candidate RGB cameras were compared with images from an engineering model HYPSO-1 RGB camera.

2. Results

In this section, the final HYPSO-2 RGB camera design is presented. Test images and justifications for the component selection are included.

2.1 HYPSO-2 RGB Camera

At the time of design, three different image sensors were available in camera modules satisfying the mechanical and electrical interface constraints. These sensors are shown in Table 3

Table 3. Candidate focal plane arrays for the HYPSO-2 RGB camera with identical electrical, mechanical, and data interfaces.

Sensor	Pixel size	Sensor size
EV76C560	5.3 µm	6.784 by 5.427 mm
MT9P006	2.2 µm	5.632 by 4.224 mm
MT9J003	1.67 µm	6.413 by 4.589 mm

See Table 2 for an overview of GSD and swath widths at different focal lengths for the potential sensors. Out of these, sensor MT9J003 with a 35 mm focal length achieves the smallest GSD while still marginally containing the hyperspectral camera swath within the short edge of its field of view.

Table 4. Specifications of the HYPSO-2 RGB camera.

Property	Value
Camera module	iDS UI-1492LE [5]
Image sensor	MT9J003
Pixel size	1.67 µm
Sensor size	6.413 by 4.589 mm
Pixel count	3840 by 2748 px
Exposure time range	0.34 - 14582 ms
Lens	Edmund Optics #33-831 [6]
Focal length	35 mm
Aperture	F/4
IR/UV cutoff filter	Edmund Optics #49-810 [7]
Nadir GSD @590 km	28 m
Field of view	10.4° by 7.7°
Nadir Swath @590 km	ca. 108 by 77 km

Depending on how many lines the push broom hyperspectral camera is scanning can the length of the resulting image vary. This means it is advantageous to have the long edge of the RGB camera oriented along-track to maximize the along-track coverage. This also minimizes the number of simultaneous captures by the RGB camera during one hyperspectral image acquisition. Thus the choice falls onto sensor MT9J003 and lens with a focal length of 35 mm. The camera module iDS UI-1492LE [5] contains this image sensor and has identical mechanical form-factor and electrical interfaces as the HYPSO-1 RGB camera. See detailed specifications about this sensor in Table 4.

To decide on a good f-number for the HYPSO-2 RGB camera lens, simultaneous images were taken with candidate HYPSO-2 RGB cameras and an engineering model HYPSO-1 RGB camera. The exposure time of the HYPSO-2 RGB camera was tuned until the resulting images exhibited similar exposure as a reference HYPSO-1 RGB image taken with close to minimum exposure time. This process was done for a set of three apertures, F/4, F/8, and F/11, giving e_{f4}, e_{f8}, and e_{f11}. Then a set of smaller exposure time values e'_{f4}, e'_{f8}, and e'_{f11} were found for which images resulted in less saturated images. See Figure 3 for images illustrating the outlined procedure. The f-number chosen for flight is the one for which

(a) 0.02 ms exposure time.

(b) F/8, 20 ms exposure time.

(c) F/8, 8 ms exposure time.

Fig. 3. Example images were taken to determine the best f-number for the HYPSO-2 RGB camera lens. (a) Engineering model HYPSO-1 RGB reference image, cropped and enlarged for easier comparison. (b) HYPSO-2 RGB image with similar visual exposure level. (c) HYPSO-2 RGB image with little saturation.

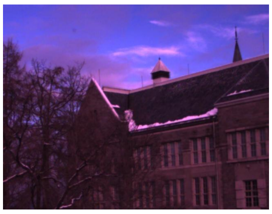
e'_{fX} is smallest leading to the least motion blur in terms of travel distance during exposure given by Equation (2), while still having a factor 5 margin towards the minimum possible exposure time of the sensor. See Table 5 for the results of the tests.

Table 5. Aperture vs. Exposure time to result in similarly exposed images as the HYPSO-1 RGB reference image, and the distance a pixel would move over ground during such an exposure.

Aperture	e_{fX}	d	e'_{fX}	d'
F/2.8	*2.5 ms*	*19 m*	*1 ms*	*7.5 m*
F/4	**5 ms**	**38 m**	**2 ms**	**15 m**
F/8	20 ms	151 m	8 ms	60 m
F/11	40 ms	302 m	16 ms	121 m

Table 5 includes an untested f-number of F/2.8 in its first row for comparison, which would be twice as fast as the F/4 lens, with exposure times halved. The minimum exposure time of the UI-1492LE camera module is 0.34 ms. The goal was to choose an f-number such that the normal operating range begins at least 5 times larger than the minimum exposure time of 0.34 ms while featuring a pixel displacement during exposure that is less than the GSD of the sensor. From Table 5 we can see that the F/4 aperture with an operating exposure time of 2 ms fulfills these conditions.

To solve the pink coloring issue, an UV/IR cut-off filter was included in the design. Figure 4 shows the effect that the IR/UV cut-off filter has on the images taken by an engineering model HYPSO-1 RGB camera. The filter is screwed into place in front of the new lens. Figure 5 shows an image of the assembled HYPSO-2 RGB camera before it is integrated into the greater payload system. Table 4 lists the choice of lens and UV/IR cutoff filter.



(a) Without UV/IR filter, 0.3 ms exposure time.

(b) With UV/IR filter, 1.0 ms exposure time.

Fig. 4. Illustrating the effect of an UV/IR cut-off filter.

Fig. 5. Image of the HYPSO-2 RGB camera.

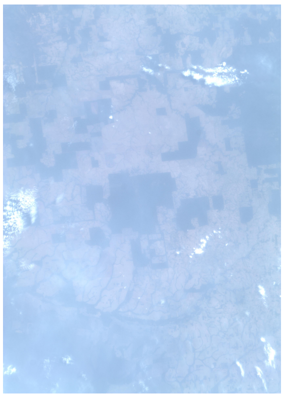
2.2 *In-orbit data*

HYPSO-2 was launched into a 592 km sun-synchronous orbit on the 16th of August 2024 on a SpaceX Falcon 9 rocket as part of the Transporter-11 rideshare mission. For the first two months of the LEOP phase, the satellite bus provider is scheduled to perform the commissioning of the satellite subsystems. Occasionally, the HYPSO team got time to check out the payload and perform testing and early operations, as part of which images were taken using both the RGB and the HSI cameras.

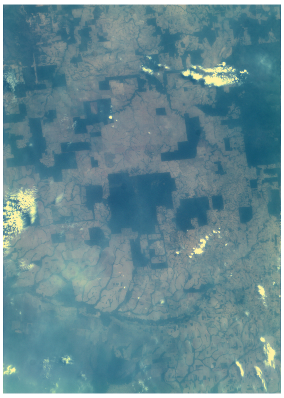
Figure 6 shows a LEOP test image from the HYPSO-2 RGB camera taken with exposure time 2 ms. The data appears hazy, but not excessively overexposed, blurry or discolored. Figure 6 also includes an atmospherically corrected true color image from the geostationary GOES West satellite taken 5 minutes earlier than the HYPSO-2 RGB image. The GOES West indicates that the haze is caused by aerosols from nearby wildfires. The image covers about 78 km by 109 km, matching the design as listed in Table 4.

3. Conclusion

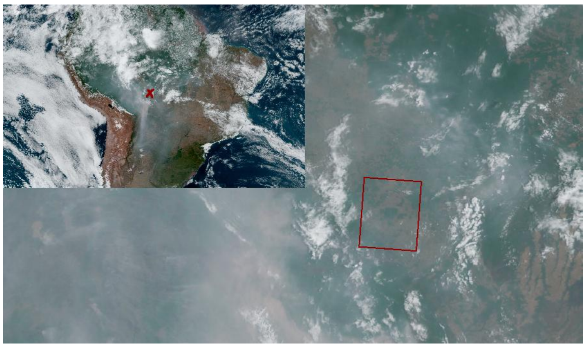
In this work, we have shown that preliminary on-orbit data from HYPSO-2 indicate that the improved RGB



(a) De-bayered raw data.



(b) Contrast adjusted.



(c) GOES West True color, 2024-09-29 14:30:00 UTC

Fig. 6. (a) and (b) HYPSO-2 RGB camera LEOP test image from 2024-09-29 14:35:07Z. (c) GOES West geostationary satellite true color imagery from 2024-09-29 14:30:00 UTC.

camera design was successful, though on-orbit calibration and validation remain to be performed. Further, we have shown a concrete example on how important it is to test a payload in as relevant conditions as close to the operational condition or environment. This is not just limited to shock and vibration testing, and thermal vacuum testing, but also sensor-specific validation. In the case of the HYPSO-1 RGB camera, this would have included testing in natural light conditions, as opposed to testing only in laboratory light conditions. The design of the HYPSO-2 RGB camera was more thought-through, and preliminary results are consistent with a successful mission.

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References

[1] Mariusz Eivind Grøtte et al. "Ocean Color Hyperspectral Remote Sensing With High Resolution and Low Latency–The HYPSO-1 CubeSat Mission". In: *IEEE Transactions on Geoscience and Remote Sensing* (2021), pp. 1–19. ISSN: 1558-0644. DOI: 10.1109/TGRS.2021.3080175. URL: https://ieeexplore.ieee.org/document/9447150.

[2] Sivert Bakken et al. "HYPSO-1 CubeSat: First Images and In-Orbit Characterization". In: *Remote Sensing* 15.3 (2023). ISSN: 2072-4292. DOI: 10.3390/rs15030755. URL: https://www.mdpi.com/2072-4292/15/3/755.

[3] iDS imaging. *HYPSO-1 RGB camera sensor*. https://en.ids-imaging.com/store/ui-1252le.html, last access: 11 October 2024.

[4] Edmund Optics. *HYPSO-1 RGB camera lens*. https://www.edmundoptics.com/p/6mm-f14-ci-series-fixed-focal-length-lens/29005, last access: 11 October 2024.

[5] iDS imaging. *HYPSO-2 RGB camera sensor*. https://en.ids-imaging.com/store/ui-1492le.html, last access: 11 October 2024.

[6] Edmund Optics. *HYPSO-2 RGB camera lens*. https://www.edmundoptics.eu/p/35mm-f40-11-hpi-series-fixed-focal-length-lens/41977, last access: 11 October 2024.

[7] Edmund Optics. *HYPSO-2 RGB camera IR/UV optical bandpass filter*. https://www.edmundoptics.com/p/m37-x-075-mounted-uvir-cut-off-filter/10283, last access: 12 October 2024.