HYPSO - 3 Hyper Spectral Imager prototypes

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1. Short background

This document describes prototype designs of a pushbroom Hyper Spectral Imager (HSI) with increased spatial resolution compared to the HSI v6 that is currently operative on the HYPer-spectral Smallsat for ocean Observation - 1 (HYPSO-1) by NTNU. The aim is to use this instrument as payload for the next generation HYPSO-3 satellite.

2. Proposed optical designs

The first optical design proposed is to use a standard 6" Schmidt-Cassegrain telescope as front optics to the HSI v6. Figure 1 shows a typical solution using the C6 Optical Tube Assembly (OTA) from Celestron. This design is equal to the SVALBIRD project where a Nikon 1000 mm reflex lens at F/11 is used as front optics. Note that the C6 has a focal length of 1500 mm at F/10. It is one aperture stop faster.

In addition, the right-angle adapter (star diagonal) makes it possible to mount the HSI v6 sideways onto the telescope, which makes the design more compact in size. The spectrograph's field of view will not be overfilled. As a result, high image quality with low stray light is expected.

The mass of the telescope is only 4.54 kg. The visual back accommodates 1.25-inch accessories, and it is mounted with a standard CG-5 dovetail (metal rail). The focus is achieved with a moving-mirror knob located behind the primary mirror. It is known to be quite sensitive, but the motion is reported to be smooth and progressive. A focus motor is recommended. The Celestron 12V DC servo focus motor is mounted directly onto the moving-mirror knob. It extends the main tube length by 77 mm and increases the total mass by 0.42 kg. It should fit within the system length of 406 mm.

This instrument should be able to detect daylight illuminated ground surface targets. Signal to Noise Ratio (SNR) calculations and sensitivity calibration must be performed prior any launch into space.

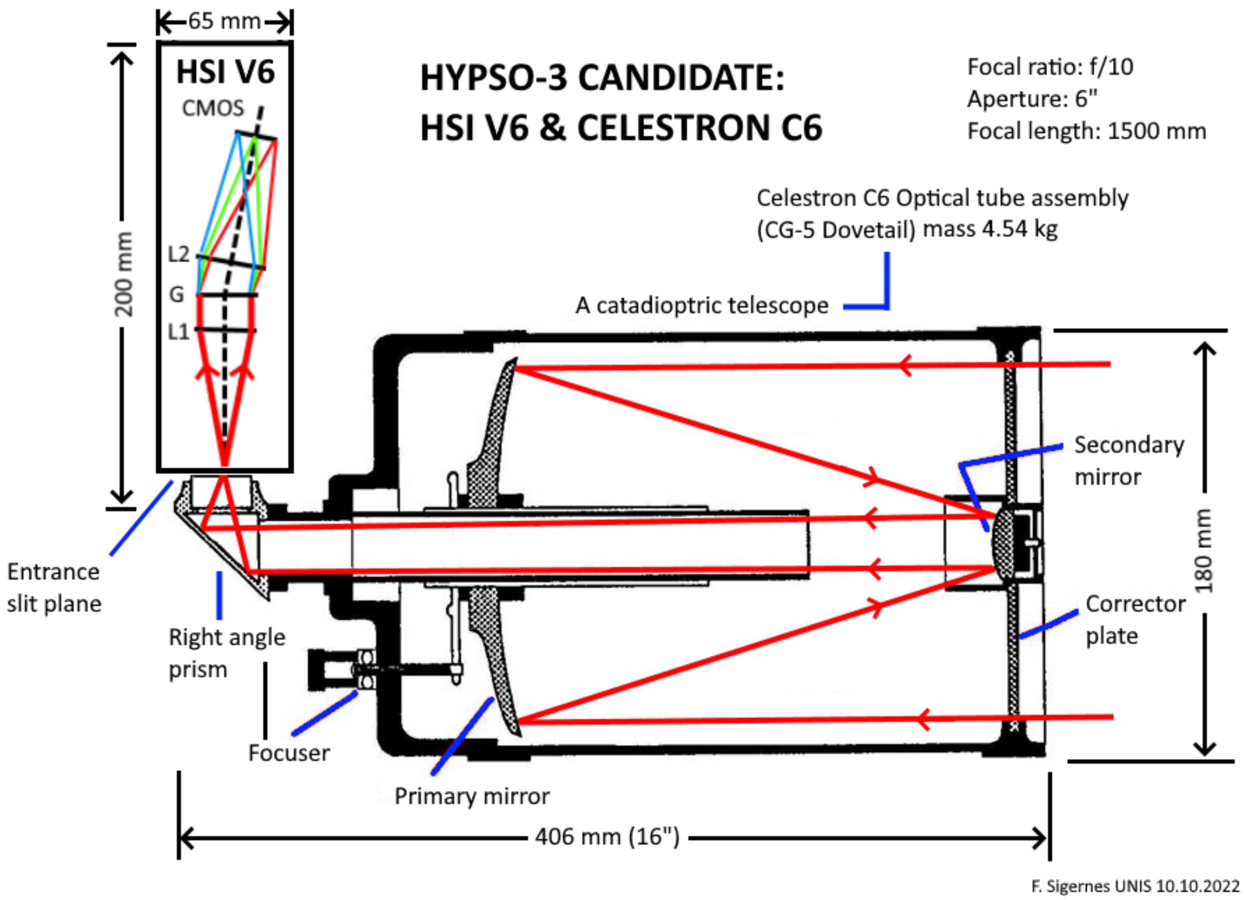

Figure 1. The 6” Celestron Schmidt-Cassegrain (C6) as front optics to the HSI v6. L1 collimator lens objective, G transmission grating, L2 camera lens objective and CMOS image sensor.

The HSI v6 payload onboard the HYPSO-1 satellite has taught us that we need to image dim ocean targets with focal ratios close to F/2.8 in order to have acceptable SNR at real time frame rates (30 spectrograms per second). [1 – 3] This is essential to build up a spectral data cube that samples the target area in just minutes without spatial under sampling. Therefore, any new design to increase the spatial resolution should rely on front optics close to F/2.8.

As emphasized, most compact catadioptric mirror telescopes do not satisfy the above criteria. For example, the design presented in the SVALBIRD project with the Nikon 1000 mm reflex lens at F/11 would require 4 stops down in aperture from F/2.8, which corresponds to 16 times less input light intensity. In other words, it becomes impossible to sample dim ocean targets in real time.

A possible telescope candidate to overcome the aperture limitations is to use the Rowe – Ackermann Schmidt Astrograph (RASA) telescope design as front optics. It basically uses an objective facing a large spherical mirror. The design is equal to the HyperStar unit – a multiple-lens corrector replacing the secondary mirror on Celestron Schmidt-Cassegrain telescopes. Depending on the size of the telescope, the focal ratios are close to F/2, up to 28 times faster than at F/10. The camera head or spectrograph in our case is placed in center front of the mirror with light entering from the sides.

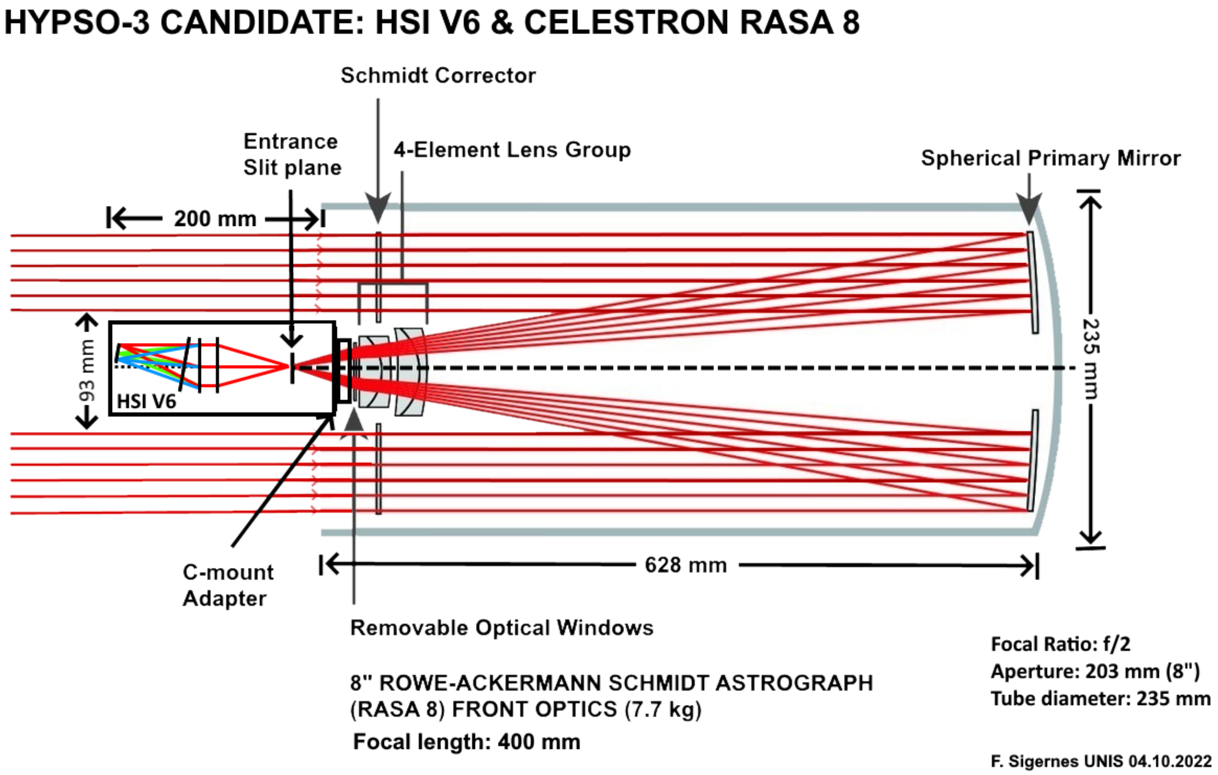

Figure 2. The 8” Celestron Rowe – Ackermann Schmidt Astrograph (RASA 8) as front optics to the HSI v6.

Figure 2 show the 8” Celestron Rowe – Ackermann Schmidt Astrograph (RASA 8) optical diagram with the HSI v6 connected to the output C-mount adapter of the telescope lens objective. This setup requires the HSI v6 to be mounted within the central obstruction diameter of 93 mm. The 200 mm instrumental length is no limitation as long as it is not obscuring the field of view on the sides. The telescope also needs to be stopped down to F/2.8 to match the HSI v6 collimator lens.

3. Spatial resolution

The instrumental parameters of the assembled instrument are equal compared to the HSI v6 on HYPSO-1, except for the increase in spatial resolution. See Table 1 for the RASA 8 and C6 telescopes.

Satellite name	Front optics	F/#	Front focal length	Cross track	Along track
HYPSO – 1	EO 50 mm	2.8	50 mm	58.06 m	500 m
HYPSO – 3	RASA 8	2.0	400 mm	7.325 m	62.5 m
HYPSO – 3	C6	10	1500 mm	1.953 m	16.667 m

Table 1. Spatial resolution HYPSO-1 versus HYPSO-3 at 500 km altitude assuming no motion between target and instrument (stationary fixed). The entrance slit is 0.05 x 7 mm^2 is size. The Sony IMX174 CMOS has 1920 x 1200 pixels. The size of the pixels is 5.86 μm square.

4. The Horiba OEM CC55 VIS- NIR Spectrograph

Another option to reduce the overall length of the system is to use a concave grating spectrograph from the company HORIBA model CC55 VIS-NIR.

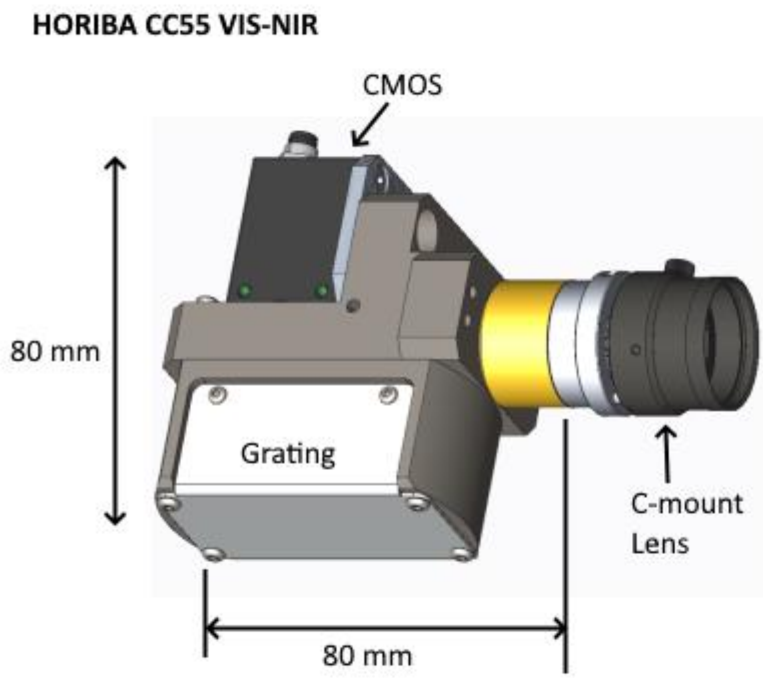

Figure 2. The 8" The HORIBA CC55 VIS-NIR Hyper Spectral Imaging camera.

HORIBA CC55 hyperspectral camera platforms have been designed with in-house optical components including a concave holographic grating and a flat surface mirror, which is built into a rugged vibration-resistant housings to ensure excellent imaging properties with reliable high performance. The CMOS detector is the same as we use on the HSI v6.

Spectral range is 350 – 1050 nm. Aperture is F/2.3 with an average spectral dispersion of 117 nm/mm. Entrance slit size may be ordered customized. The spectral bandpass is less than 3.5 nm with a 25 µm wide slit. Height of slits are maximum 11.2 mm.

The instrument optical performance may easily be compared to our HSI v6, but it is much more compact with less optical components. The imaging quality is suspected to be better, especially on the blue and far-red side of the spectrum. The system height with the C6 telescope is not enhanced as it is with the HSI v6, since the height of the CC55 is only 80 mm. The same applies to the overall system length when connected to the RASA 8 telescope.

5. Prototype components cost list

Item	Parts	Description	Qty	Item $	Sum $
1	HSI v6	Hyper Spectral Imager v6	3	3,200	9,600
2	RASA 8	8” Celestron Rowe-Ackermann Schmidt OTA	3	2,079	6,237
3	C6	6” Celestron Schmidt-Cassegrain OTA	3	800	2,400
4	Focus Motor	Celestron Focus Motor v2	3	260	780
6	HORIBA CC55	OEM Concave grating spectrograph	3	?	?
				Total	**?**

Table 2. Prototype Components costs. Item 1 - 4 costs are from the company B&H. All part costs are obtained in early October 2022.

All parts described here are from commercially available companies without additional freight costs.

6. Construction and tentative timetable

Instrument option	Length (mm)	Tube diameter (mm)	Mass (kg)
HSI v6 + C6	406	180	5.506
HSI v6 + RASA 8	905	235	8.666
CC55 + C6	406	180	?
CC55 + RASA 8	785	235	?

Table 3. Approximate size (tube) and mass for Prototype (PT) HSI HYPSO-3

Action	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Order parts	x	x										
Assembly (2 x PT)		x	x	x								
Prototype testing				x	x	x						
Ruggedization (FM)				x	x	x	x	x	x	x	x	
Calibration							x			x	x	
Testing FM										x	x	x
Payload delivery												x

Table 4. Estimated monthly timetable for construction of HYPSO-3 HSI. PT is Prototype. FM is the ruggedized Flight Model.

The above 1-year timetable includes parallel construction of 2 Prototype (PT) instruments using either the RASA 8 or the C6 telescope, one at UNIS and the other by students at NTNU. After assembly and testing, ruggedization of the Flight Model can start by the mechanical department at NTNU. Calibration should be conducted on all 3 instruments. Note that the optical lab at UNIS is setup to calibrate narrow field of view – large aperture instruments. Delivery to bus provider should then occur in month 12.

Whether to use the HSI v6 or the CC55 should be decided in week 5 -6 after assembly and testing.

Conclusion

One low and high throughput design HSI using commercially available components are proposed and described that should be capable of high-resolution imaging from spaceborne platforms. It is suspected that the main challenge is to ruggedize the instrument for a life in space, including stress from external forces, vibrations during launch, temperature changes and outgassing in orbit etc.

References and links

1. M. E. Grøtte, R. Birkeland, E. Honore-Livermore, S. Bakken, J. L. Garett, E. F. Prentice, F. Sigernes, M. Orlanic, J. T. Gravdahl and T. A. Johansen, "Ocean Color Hyperspectral Remote Sensing With High Resolution and Low Latency--The HYPSO-1 CubeSat Mission," in *IEEE Transactions on Geoscience and Remote Sensing*, https://doi.org/10.1109/TGRS.2021.3080175.
2. E. F. Prentice, M. E. Grøtte, F. Sigernes, and T. A. Johansen, "Design of a Hyperspectral Imager Using COTS Optics for Small Satellite Applications," in International Conference on Space Optics - ICSO 2020. SPIE, 2021. https://doi.org/10.1117/12.2599937
3. M. Henriksen, E. Prentice, C. van Hazendonk, F. Sigernes, and T. Johansen, "Do-it-yourself VIS/NIR pushbroom hyperspectral imager with C-mount optics," Opt. Continuum 1, 427-441 (2022). https://doi.org/10.1364/OPTCON.450693

Prioritized shopping list to start the project

Item	Parts	Description	Qty	Item $	Sum $
1	C6	6" Celestron Schmidt-Cassegrain OTA	3	840	2,520
2	Adapters	C-Mount to 1.25-inch barrel adapter	3	16	48
3	GOTO mount	iOptron Computerized Az-El mount	1	1,148	1,148
4	Focus Motor	Celestron Focus Motor v2	3	210	630
5	RASA 8 *	8" Celestron Rowe-Ackermann Schmidt OTA	3	2,079	6,237
6	HORIBA CC55	OEM Concave grating spectrograph	3	?	?
				Total	**10,583+?**

Table 2. Prioritized shopping list 25.01.2023.

* Note that the RASA 8 comes with C-mount adapters as included accessories. OTA means Optical Tube Assembly (OTA) which is only the telescope. NTNU will need one motorized Azimuth – Elevation unit mounted to a heavy-duty tripod to test assembled system. This is item 3 in the above table. Also consider transport cases when sending OTAs etc. to UNIS.