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.

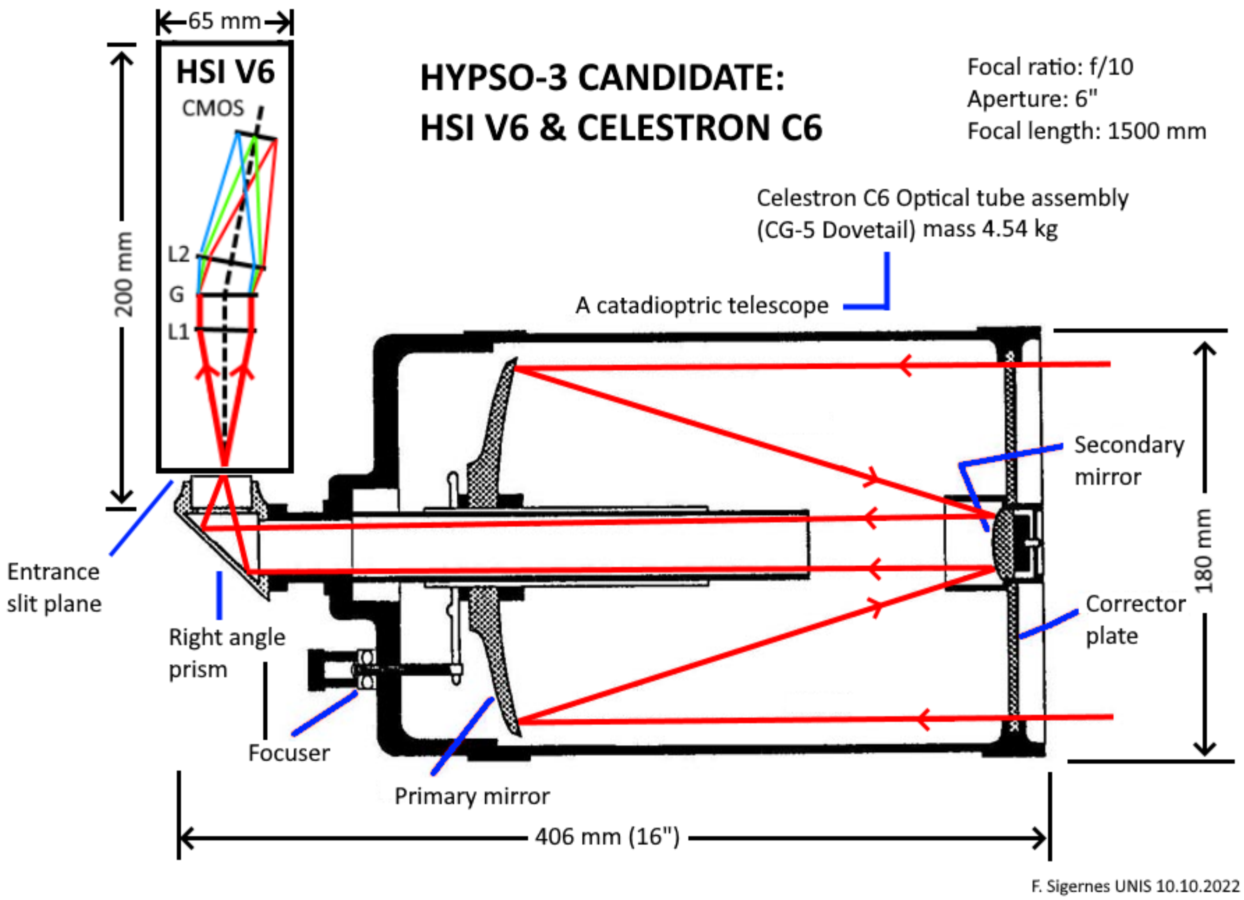


Figure 1. The 6" Celestron Schmidt-Cassegrain (C6) as front optics to the HSI v6. L1 collimator lens objective, G transmission grating, L2 camera lens objective and CMOS image sensor.

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.

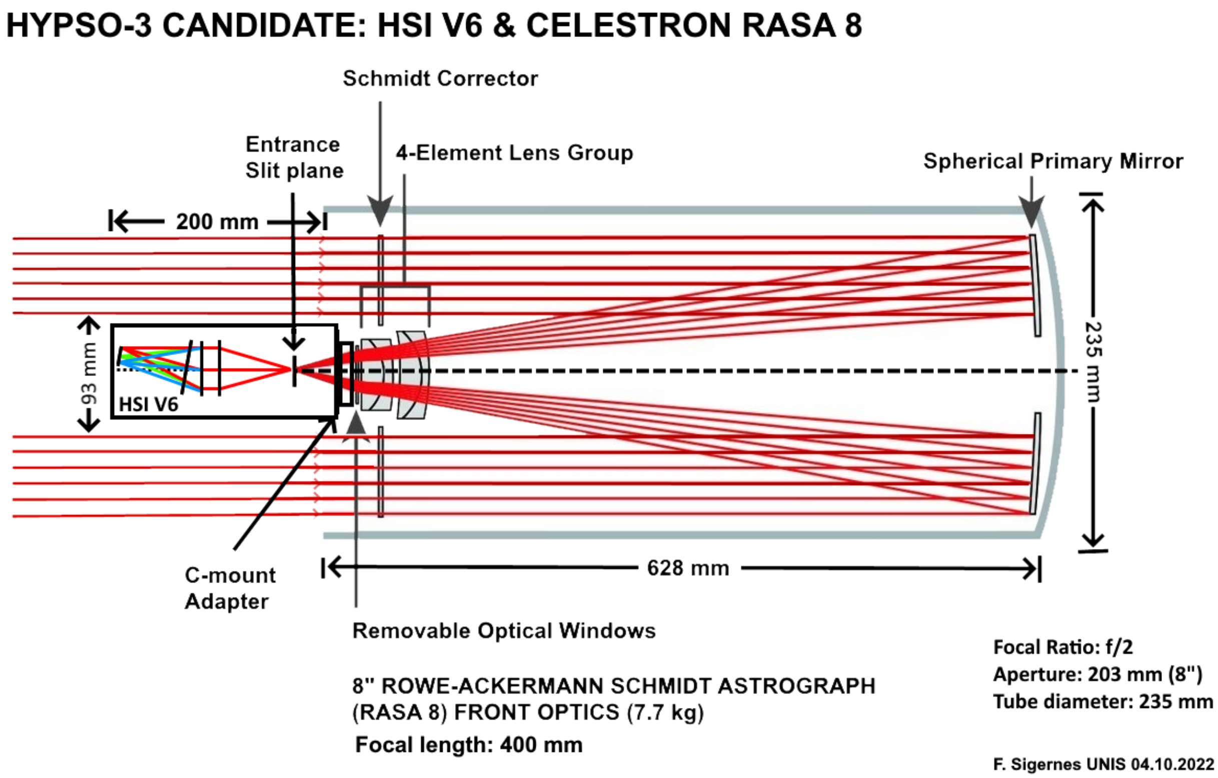


Figure 2. The 8" Celestron Rowe – Ackermann Schmidt Astrograph (RASA 8) as front optics to the HSI v6.

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

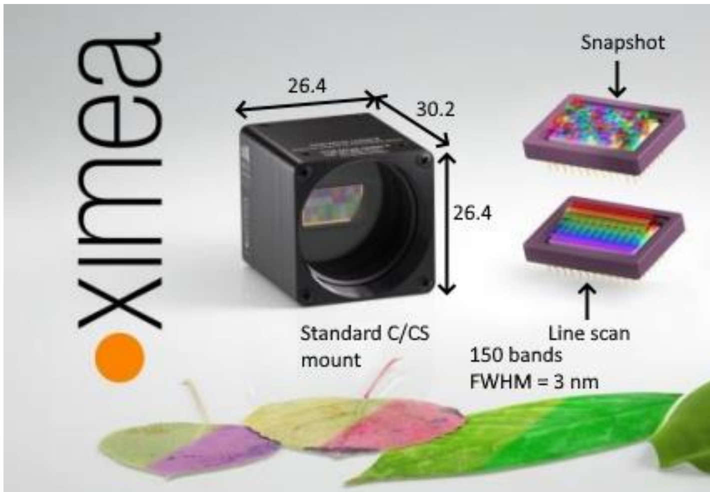
The instrumental parameters of the assembled instrument are equal compared to the HSI v6 on HYPSO-1, except for the increase in spatial resolution. See Table 1 for the RASA 8 and C6 telescopes.

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. New technology

Another option to reduce the overall length of the system is to use new technology hyperspectral imagers from the company XIMEA GmbH. One candidate could be the line scan model xiSpec LS150-VN2 connected to the RASA 8 or C6 telescope.



Value	Description
Sensor	AMS / CMOSIS CMV2000 mono
Resolution	2048 x 1088, 2.2 Mpix
Pix. size [µm]	5.5
ADC [bits]	10, 8
Sensor size / diagonal [mm]	11.3 x 6.0
Optical size	2/3 "
Fps	170 (USB3.0), 340 (PCIe X2G2)
Power typ. [W]	1.5 (xiQ)

Figure 2. The 8" The XIMEA Hyper Spectral Imaging camera sensor with specifications. Dimensions are in mm.

The camera head consist of Fabry – Perrot interference filter array stacked on top of the CMOSIS 5.984 x 11.264 mm^2 sized CMOS sensor. The spectral bandpass is 3 nm with 150 bands across the 470 – 900 nm spectral range. Estimated spatial resolution is 6.875 x 34.375 m^2 with RASA 8 and 1.833 x 9.167 m^2 with C6. Each spectral band is 1x5 pixels in size.

The spectral data cube is different compared to the standard pushbroom technique we use on the HSI v6. A standard hypercube reconstruction requires re-organization by vector tracking objects in each raw data frame to obtain target point spectra.

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
5	xiSpec	XIMEA Hyperspectral Imager LS150-VN2	3	19,530	58,590
6	xiSpec starter kit	XIMEA xiSpec2-kit-35-TLE-TRI	2	1,167	2,334
				Total	**79,941**

Table 2. Prototype Components costs. Item 1 - 4 costs are from the company B&H. Item 5 – 6 are from XIMEA. 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
xiSpec + C6	406	180	4.992
HSI v6 + RASA 8	905	235	8.666
xiSpec + RASA 8	736	235	8.152

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 xiSpec line scanner should be decided in week 5 -6 after assembly and testing. Note the xiSpec option is making the full use of the RASA 8 telescope at F/2.

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