SPECTRAL REQUIREMENTS FOR THE DEVELOPMENT OF A NEW HYPERSPECTRAL RADIOMETER INTEGRATED IN AUTOMATED NETWORKS - THE HYPERNETS SENSOR

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ABSTRACT

Networking of automated instruments on unmanned platforms has proved to be the most effective way to provide validation data for earth observation optical missions. However, with most current networks, such as AERONET-OC [1] for water and RADCALNET for land [2], the validation data are multispectral and/or limited in viewing geometries, resulting in modelling associated uncertainties to cover all spectral bands of all sensors and to correspond to satellite viewing geometries. Therefore, the HYPERNETS Project is developing a new hyperspectral radiometer to be integrated in automated networks. The main goal of the project is to acquire hyperspectral measurements of water and land reflectance and validate every optical earth observation satellite remote-sensing sensor in the Visible-Near Infrared (VNIR) and Short-wave Infrared (SWIR) spectral range. The present study reports the spectral characteristics of current and future earth observation missions. These characteristics represent the main drivers for the design of the HYPERNETS sensor.

Index Terms— Hyperspectral, validation data, land, water, network

1. INTRODUCTION

Networking of automated instruments on unmanned platforms, e.g. AERONET-OC [1] for water and RADCALNET [2] for land, has proved to be the most effective way to provide validation data for earth observation optical missions. The re-use of data from each site for many optical missions gives a huge economy of scale. The existing AERONET-OC network is based on multispectral instruments and the RADCALNET system provides 10 nm spectral resolution nadir viewing reflectance. Both networks require therefore modelling associated uncertainties to cover all spectral bands of all sensors and to correspond to the satellite viewing geometries. However, with the recent advances in opto-electronics, it is now possible to develop high performance miniaturized hyperspectral spectrometers with reduced price. This is the main goal of the HYPERNETS project. The HYPERNETS sensor, and associated pointing system and embedded spectral responsivity stability checking device, will provide water and land high spectral resolution directional reflectance validation data for every Visible-Near Infrared (VNIR) and and Short-wave Infrared (SWIR) spectral band of every optical earth observation satellite remote-sensing sensor. The concept of the network is similar to that of existing validation networks such as AERONET-OC, which successfully provides multi-spectral validation data, but it ensures hyperspectral measurements. The sensor design, and particularly the spectral characteristics, of the HYPERNETS instrument is therefore mainly based on the characteristics of current and future VNIR and SWIR earth observation passive satellite optical sensors. The present study reports these characteristics and discusses the feasibility to translate these into sensor requirements for the design of the HYPERNETS instrument.

Table 1 provides a non-exhaustive list of optical sensors on board of current and future satellite missions that could be validated with HYPERNETS. Operational earth observation missions are mainly multi-spectral but all together they provide spectral information over a wide range in the VNIR and SWIR spectral domain. With the advances in hyperspectral sensors, the few current hyperspectral earth observation missions (e.g., the Compact High Resolution Imaging Spectrometer, CHRIS, launched on board of PROBA-1) are expected to be joined in a near future by several new hyperspectral satellite missions (e.g., the Italian mission "PRecursore IperSpettrale della Missione Applicativa", PRISMA, the German Environmental Mapping and Analysis Program, ENMAP, the Japanese mission Hyperspectral Imager SUIte, HISUI, and, the joint Spaceborne Hyperspectral Applicative Land and Ocean Mission by the Israeli and Italian space agencies, SHALOM). Other hyperspectal sensors are currently in their study stage but are expected to be launched in the next following years, for instance, the french HyPXIM sensor, the NASA's Hyperspectral Infrared Imager, HyspIRI, and, the two phase A ESA missions which may become Sentinel-

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10. The design of the HYPERNETS sensor should take into account the VNIR and SWIR spectral range as well as the spectral resolution of current and future multispectral and hyperspectral earth observation satellite missions. Fleets of current and future nano-satellites, such as, Landmapper, KEOSat, Dove and the research nano-satellites AALTO-1 (Finnish research nano-satellite from the Aalto University) should also be considered. The spectral characteristics of atmospheric satellite sensors such as the Sentinel-5/UVNS and the future Sentinel-4/UVN sensors may also be considered but are not the main priority of HYPERNETS. According to Table 1, HYPERNETS should already fulfil the spectral requirements of at least 40 sensors on board of more than 300 current and future satellites.

The next sections report the requirements for the sensor design from the different sensors listed in Table 1, particularly the spectral range (Section 2) and resolution (Section 3). The HYPERNETS instrument will achieve significant cost reductions compared to existing instrument systems, while at the same time achieving performance improvements. Therefore both sections highlight the challenges that are faced when dealing with cost constraints and hyperspectral sensors. The conclusion sums up the final requirements for the sensor design in terms of spectral specificities.

2. SPECTRAL RANGE

Figures 1 and 2 show the spectral range of the satellites mentioned in Table 1. Several future sensors will provide images at spectral bands down to 380 nm (i.e., HyspIRI, GOCI II and SABIA-MAR). The current Second generation GLobal Imager (SGLI) on board of the Japan satellite GCOM-C also provides data at 380 nm. Several future sensors such as OCI/PACE, GOE-CAPE and ACE are expected to have a spectral range that goes below 380 nm. World View 110 (WV110) on board of World View 2 and 4 also cover a spectral range that goes below 350 nm but it corresponds to the minimal wavelength range of the spectral response function of the broad blue band. Although studies have shown the needs in spectral information below 380 nm (e.g., for the determination of some phytoplankton functional types and/or particle size structure [5]), it is not clear whether an adequate atmospheric correction can be developed for satellite data at wavelengths below 400 nm. Indeed the high absorption of the ultraviolet in the atmosphere will render the atmospheric correction even more difficult, particularly for water applications were the water leaving radiance is very low compared to the atmospheric contribution. Hence the need for validation data below 380 nm, which would significantly increase the cost of the sensor, remains questionable. Note also that present results does not account for out-of-band response.

In the NIR, most satellites provide spectral information up to 900 nm (Fig. 1). Above 1000-1020 nm, the spectral responsivity of standard VNIR detectors based on silicon semi-

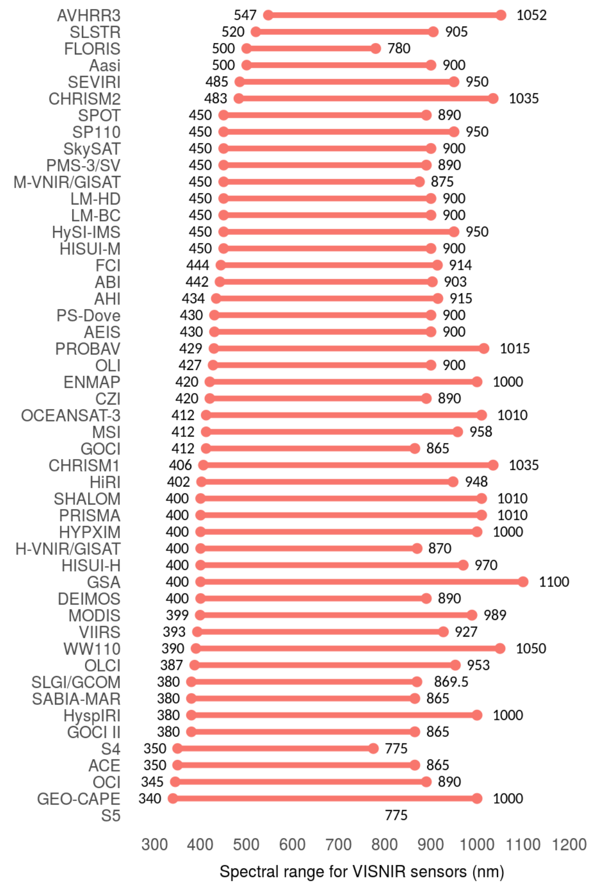

Fig. 1: VNIR spectral range of several earth observation satellite sensors (see Table 1) that need to be considered for the development of the HYPERNETS sensor design.

conductor technology drops rapidly. Therefore, to measure the signal at higher wavelengths, another detector is required increasing the cost of the sensor.

The SWIR spectral range is largely constrained by the cost of the detectors. Indeed, SWIR detectors with a spectral range up to 2500 nm are significantly more expensive than the detectors covering the 900-1700 nm spectral range. However, as mentioned by Transon et al. [6], who reviewed the needs in hyperspectral remote sensing missions, spectral information in the 1700-2500 nm range is almost mandatory. Figure 2 also confirms that most earth observation sensors provide spectral information up to 2500 nm. Hence, the spectral requirements for a hyperspectral sensor in the 1700-2500 nm spectral range is confirmed but may be constrained by the cost of the instrument.

3. SPECTRAL RESOLUTION

In the past the spectral resolution of satellite sensors was limited by the technical and practical constraints resulting

Table 1: Non-exhaustive list of multispectral and hyperspectral earth observation satellite missions to be considered for the development of the HYPERNETS sensor design. The table provides information about the swath, spatial resolution, number of bands (♯ bands), orbit (P: Polar, G: Geostationary), status of the mission (O: Operational, P: in Preparation, and, C: Considered), approximate number of satellites (♯ sat.) and additonal comments (Com., cap, constr. a., point., NS and spat. res. stand for Commercial, capability, constrained acces, pointing, nanosatellites and spatial resolution, respectively). This table is compiled using the best available information at the time of writing (i.e., April 2018) but may be subject to rapid change. Due to space limitations, information sources couldn't be added to the table. However most of the information was provided by the Observing Systems Capability Analysis and Review Tool (OSCAR) from the World Meteorological Organization (WMO) [3] and the Satellite Missions Database from the Earth Observation Portal of ESA [4]. Both sites also refer to the websites of the missions and space agencies.

Sensor/Satellite(s)	**Swath (km)**	**Spat. Res. (m)**	**♯ bands**	**Orbit**	**Status**	**♯ sat.**	**Comments**
HiRI/Pléiades	120	3	4	P	O	2	Com., cross and along-track point.
OLCI/Sentinel-3	1270	300	21	P	O	2	
SLSTR/Sentinel-3	1400	500	6	P	O	2	
MSI/Sentinel-2	290	10-60	13	P	O	2-3?	
MODIS/Aqua-Terra	2230	1000	20	P	O	2	500 and 1000 m spat. Res
OLI/Landsat-8	185	30	8	P	O	1	
HYC/PRISMA	30	30	173	P	P	1	
MUS-VNIR/SABIAMAR-A	200/2200	200/1100	12	P	P	2	Some bands@200m spatial res.(coastal)
MUS-SWIR/SABIAMAR-B	2200	1100	4	P	P	2	
FLORIS/FLEX	150	300	280	P	C	1	
SGLI-VNIR/GCOM-C	1150	250(1000)	11	P	O/P	3	2 polarimetric channels@1 km spatial res., others 250m
SGLI-SWIR/GCOM-C	1400	1000(250)	4	P	O/P	3	1630 nm@250 m spat.res and 200 nm $\Delta\lambda$, else 1km spat.res and 20-50nm $\Delta\lambda$.
S10			NA	P	C	1	
HSI/ENMAP	30	30	244	P	P	1	
CHRIS-M1/PROBA-1	14	36	63	P	O	1	Point., BRDF acquisitions of the same area@+/-55 , +/-36 and 0 θ_v along the same orbit
CHRIS-M2/PROBA-1	14	18	18	P	O	1	Point.
WorldView110/WV2-3	16.4	1.84	16	P	O	2	Com., Stereo cap. along-track and cross-orbits
SpaceView110/WV4	13	1.24	6	P	O	1	Com., Stereo cap. Along-track and cross-orbits
Vegetation/PROBA-V	2285	100(200)	4	P	O	1	VNIR@100 m, SWIR@200m
AEIS(-A)/KOMPSAT3(-A)	15(12)	2.8(2)	4	P	O	2	Constr. a., point.
HySI-T/IMS-1	130	500	64	P	O	1	Constr. a.
HISUI-M/ALOS-3	90	5	4	P	P	1	
HISUI-H/ALOS-3	30	30	185	P	P	1	
GSA/Resurs-P	30	60	216	P	O	3	
CZI/HY	500	250/1100	4	P	O/P	4	
VIIRS/NOAA-JPSS	3000	750	11	P	O/P/C	4(2?)	
AVHRR3/METOP-NOAA	2900	1100	3	P	O	2	
SEVIRI/METEOSAT	full disk	3000	3	G	O	4	
GOCI/COMS-1	2500	500	8	G	O	1	
GOCI II/GEO-KOMPSAT	1200x1500	250/1000	13	G	P	1	
FCI/MTG	full disk	500-2000	8	G	C	4	Evolution of SEVIRI
HyS-VNIR/GISAT	250	320	60	G	C	1	Constr. a.
HyS-SWIR/GISAT	250	192	150	G	C	1	Constr. a.
AHI/HIMAWARI8-9	full disk	500-2000	6	G	O	2	645 nm@500m, SWIR@2km and others at 1km
ABI/GOESS	1000	1000	6	G	O/C	4	
HiRAIS/Deimos-2	12	4	4	P	O	1	
OPS/ASNARO	10	2	6	P	O	1	
PMS-3/Superview	12	2	4	P	O	4	
NAOMI/SPOT6-7	14-25	8	5	P	O	2	Stereo cap. along-track and cross-orbits
SkySAT/SkySAT	8	2	4	P	O	14	Com.
AaSI/AALTO-1		240	20	P	O	1	NS, spectral bands varies from 6 to 20 (but +60 is possible)
PlanetScope/Dove		3.5	4	P	O	175	NS, Landsat filters, copied the $\Delta\lambda$ from OLI
LM-BC/Landmapper		22	5	P	O/C	10	NS, Landsat filters, copied the $\Delta\lambda$ from OLI
LM-HD/Landmapper		2.5	5	P	C	20	NS, Landsat filters, copied the $\Delta\lambda$ from OLI
KEOSat			NA	P	O	?	NS from Karten Space
2HOPSAT/NASA			NA	P	C	50	Future NS developed at NASA
SHALOM	10	10	241	P	C	1	Com., 30° max. roll angle off-nadir from swath centre
HyspIRI	145	30	213	P	C	1	
HYPXIM-CNES	15	8	210	P	C	1	
OCI/PACE	100	1000	116	P	C	1	
OCM/OCEANSAT-3	1440	360(1080)	13	P	O/P	2	780-1010nm@1080 m spat.res others 360 m
ACE/OES	116.6deg	1000	26	G	C		
HRMX-VNIR/GISAT		50	6	G	C	1	
GEO-CAPE/?		250-375	155	G	C	1	
UVN/MTG/Sentinel-4		$<$10000	1500	G	P	2	Atmospheric applications
UVNS/Meteop/Sentinel-5	2715	7000	3936	P	P	3	Atmospheric applications

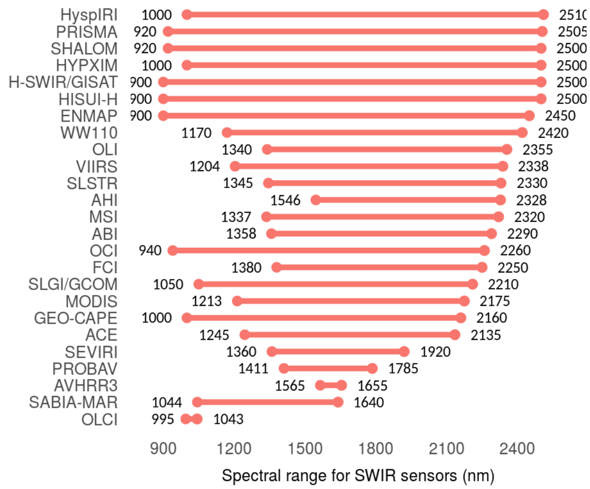

Fig. 2: SWIR spectral range of several earth observation satellite sensors (see Table 1) that need to be considered for the development of the HYPERNETS sensor design.

from the direct trade-off between spatial and spectral resolution. With the advances in optical remote sensing, recently launched satellites provide now narrower and more bands often covering a broader spectral range in the VNIR and SWIR. For instance, the ocean color sensors such as MODIS/AQUA and VIIRS/NOAA have spectral resolutions in the VNIR between 10 and 50 nm while the recently launched OLCI sensor on board of Sentinel-3A and 3B has spectral resolutions varying between 2.5 and 20 nm. Figures 3 and 4 show the number of total spectral bands versus the minimum spectral resolution in the VNIR and SWIR spectral range (here defined by the minimal band width encountered over all the spectral bands of the sensor), respectively. As expected, most sensors with a very high spatial resolution (< 10 m) are limited to a few wide RGB-NIR bands with a relatively low spectral resolution (> 50 nm, e.g., HiRi on board of Pléiades, World-View110 on board of WorldView 2 and 4 and Vegetation on board of Proba-V). Only a few number of very high spatial resolution satellites (e.g., some of the PlanetScope/Dove instruments, LandMapper-HD or SpaceView 110, SP110, on board of WorldView 3) show some bands with spectral resolutions ranging between 20 and 50 nm. Most medium (100-500 m) and high (10-100 m) spatial resolution satellites show a minimum spectral resolution varying between 5 and 10 nm. The current OLCI sensors on board of the Sentinel-3 satellites are however an exception with their 2.5 nm spectral resolution band at 767.5 nm for the fluorescence measurements over land. CHRIS is also an exception when operating in "MODE 1" with its 63 spectral bands at spectral resolutions varying between 1.2 and 12 nm. The future hyperspectral OCI sensor on board of PACE is expected to provide spectral information in the 345-890 nm spectral range at a spectral resolution ranging from 2 to 5 nm.

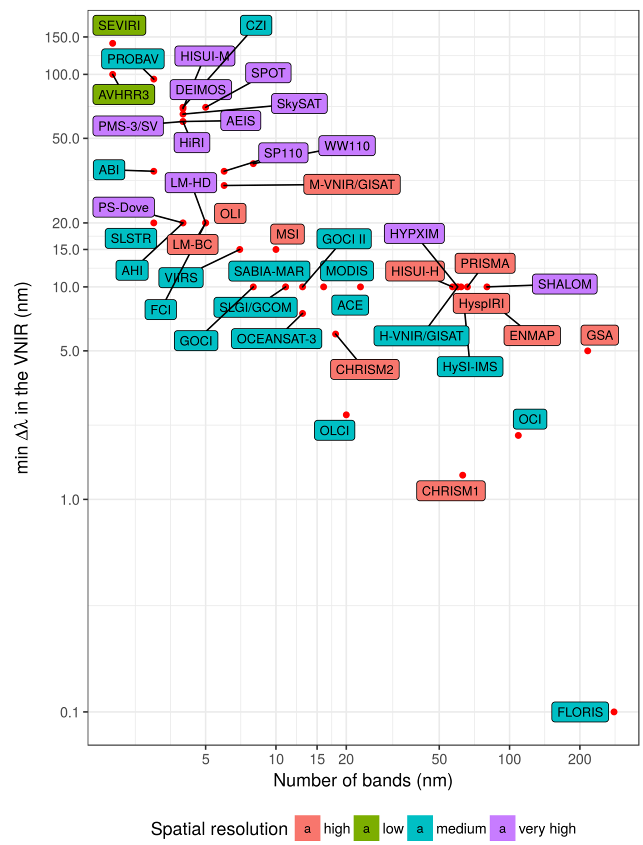

Fig. 3: Minimum spectral resolution ($\Delta\lambda$) of all bands in the VNIR spectral range (380-1020 nm) versus the number of bands in the VNIR. NOTE: The number of bands in the VNIR for HYPXIM, FLEX/FLORIS, SHALOM and HyspIRI are approximate values based on the total number of bands and the spectral resolution.

In the SWIR spectral range (Fig. 4), most sensors have minimal spectral resolutions of 10 nm or higher. Only OCI on board of PACE is expected to have spectral resolutions below 10 nm (i.e., 6 nm). For the design of their hyperspectral mission HYPXIM (400-2500 nm), the French Centre National d'Etude Spatial (CNES) collected the requirements from several scientific user groups and from the defence [7]. Results from this survey were also used to shape the mission requirements defined for the hyperspectral SHALOM mission [8]. According to their survey, the spectral resolution for a hyperspectral earth observation data should remain below 10 nm, in the VNIR and SWIR spectral range, for all scientific domains.

Hence to meet the spectral resolution of most current and future earth observation sensors, hyperspectral validation data should provide data at 2 nm or better in the VNIR, and 6 nm or better in the SWIR. Note however that according to Zibordi et al. [9], an accurate validation of the OCI/PACE ocean color data in the blue spectral region requires *in situ* validation data at a sub-nanometer spectral resolution. The minimum spectral resolution of FLORIS/FLEX (0.1-2 nm) as well as the atmospheric sensors Sentinel-4 (0.2-0.5 nm) and Sentinel-5 (0.4-1nm) will be difficult to achieve if the instrument needs to remain low-cost.

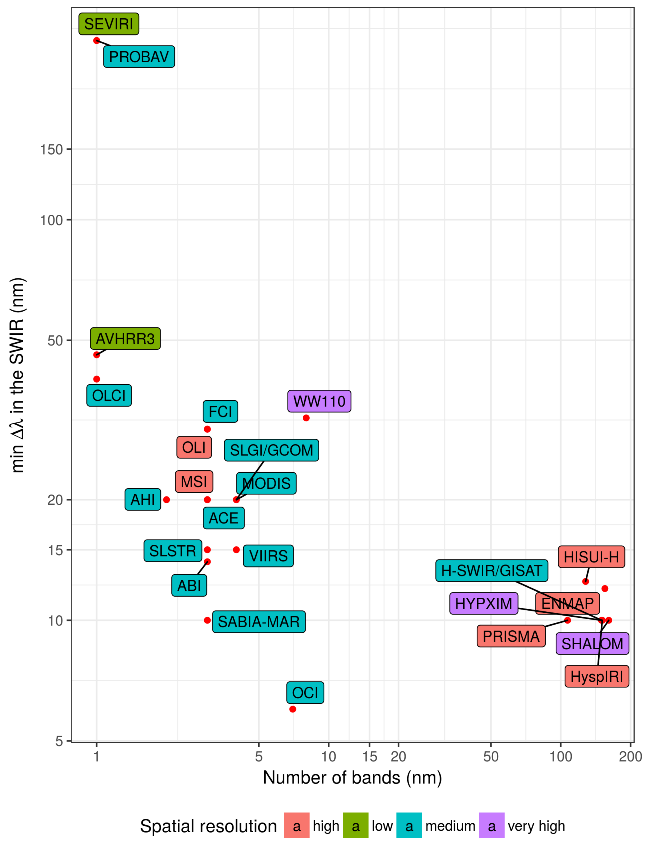

Fig. 4: Same as Fig. 3 but for the SWIR (1000-2500 nm) spectral range.

4. CONCLUSION

The present document discusses the spectral requirements for the design of the HYPERNETS instrument. The spectral characteristics of the final sensor design will, however, also be limited by cost constraints, engineering design and available components. In terms of spectral range, and within the constraints of the system cost, it seems realistic to provide hyperspectral data between 380 and 1020 nm. Below 380 nm the cost may greatly increase and the need for validation data remains questionable due to the lack of accurate atmospheric correction and the lack of sunlight at the earth surface at short Ultra-Violet wavelengths. In the SWIR spectral range, the HYPERNETS sensor should cover the 1000-1700 nm spectral domain. Hyperspectral data up to 2500 nm are highly desirable but may not meet the low-cost constraints. A 5 nm spectral resolution in the VNIR may be sufficient for most sensors. However 1 nm and even sub-nanometre spectral resolution is desired to provide validation data for all future hyperspectral satellite missions. In the SWIR, a spectral resolution ranging from 5 to 10 nm appeared to be sufficient.

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