Hyperspectral cameras designs and constraints for small satellite private EO missions: perspectives for coastal water quality monitoring applications and markets, the ENTRUST mission case

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ABSTRACT

Hyperspectral cameras and sensors have recently matured a lot and nowadays are widely used in monitoring the Earth for private industrial purposes. Fields of interest include agriculture and forestry monitoring, food control, medicine, mineralogy, environmental surveillance etc. However, even though in space this technique has been developed and tested from the late 80s to 2000, commercial satellites embarking Hyperspectral cameras for monitoring purposes are still in their infancy.

This paper presents and analyses the ENTRUST project which aims to address the feasibility of an operational downstream service, which exploits Copernicus services and Hyperspectral data from a small satellite in providing robust monitoring and analysis of the coastal water quality parameters, as they are defined in the Art. 2 of the Water Framework Directive from the European Commission (WFD; Directive, 2000/60/EC). The current study investigates the main trade-offs and constraints in terms of hyperspectral instrumentation as well as market considerations, as both are strongly interrelated in the case of a privately owned mission.

Keywords: Hyperspectral, imagery, visible detectors, cubesat, water quality, water monitoring, coastal water, hyperspectral camera

1. INTRODUCTION

Coastal zones serve as the interface between the land and marine environments. The length of the world's coasts exceeds 1,6 million kilometers, and 84 percent of the world's countries have a coastline.

Globally, coastal zones are more densely inhabited than inland regions, have faster rates of population increase and urbanization, and accumulate economic assets along with essential infrastructures[1]. The low-elevation coastal zone, which is defined as the continuous and hydrologically linked zone of land along the coast with an elevation above sea level of less than 10 meters, comprises just 2% of the world's total area, but is home to 10% of the global population[2]. In response to population expansion and coastward migration linked with the worldwide trend of urbanization, it is expected that the coastal population will continue to increase in the future years. The global population is projected to reach 8.5 billion in 2030 and 9.7 billion in 2050[3], and the majority of the world's megacities are located in the coastal zone, the majority of them in river deltas[4]. In addition to unique economic, physical, and historical variables, the concentration of densely occupied agricultural regions in well-watered, productive deltas and coastal plains drives coastal migration[5].

Coastal zones provide a considerable economic worth. For example, marine transport is vital to the global economy since more than 90 percent of global trade is handled by water, with a significant percentage of maritime routes in the coastal ocean. In 2010, the global ocean economy was worth 1.5 trillion dollars, with a significant contribution from oil and gas companies, ports and marine equipment, and ocean-based sectors dominated by fisheries and tourism[6]. In addition to these well-established activities, other ones, such as marine aquaculture, ocean renewable energy, and maritime safety and surveillance, are expected to see growth in the future decades[6].

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The ocean economy is expected to rise to more than three trillion dollars by the year 2030, according to conservative forecasts. A significant portion of this figure will come from coastal tourism, offshore oil and gas, and port operations. Between the years 2010 and 2030, it is anticipated that marine aquaculture would expand at a pace of 5.7 percent on a yearly basis.

Coastal environments are home to a diverse array of plant and animal life, both on land and in the water. Marine coastal habitats are among the most productive ecosystems on the planet, and they offer people a wide variety of social as well as economic benefits. They are responsible for producing ninety percent of the world's fisheries and roughly eighty percent of the marine fish species that are known[7]. Reefs, mangroves, and sand dunes all play a part in controlling the environment and protecting the coastline[8]. One way in which they do this is by significantly reducing the force of wind-driven waves. Coral reefs and river estuaries both have a high biomass production, making them two of the most biodiverse and species-rich environments on the planet.

As a result, coastal zones have a significant amount of value from a social, economic, and ecological perspective[9]. They are contributing to human society in a variety of ways, including the provision of food, energy, and other resources; the protection of coastlines; the promotion of ocean recreation, tourism, and coastal livelihoods; the upkeep of water quality; the treatment of waste; the promotion of biogeochemical cycling and regulatory services; the support of both the green and blue economies; and, most importantly, the upkeep of the fundamental global life support systems.

However, coastal areas are vulnerable to a variety of threats, some of which originate naturally and others are the result of human activity. Extreme conditions in the natural environment can play a role in the development of natural hazards. For example, marine heat waves can lead to coral bleaching and fish mortality, large waves and extreme sea levels can cause coastal flooding, erosion can degrade ecosystems and habitats. Several of these problems are made worse by climate change and the resulting warming, as well as the rise in sea level and an increase in hazardous algal blooms[10]. On the other hand, coastal hazards that are caused by human activity include maritime pollution, unsafe maritime conditions, poor water quality, eutrophication, overfishing, degradation or loss of marine and coastal ecosystems[11]. Maritime pollution is the discharge of pollutant substances into the ocean from ships. Therefore, the variables that cause maritime and coastal dangers may be found anywhere.

So, several steps must be made in order to maintain the health of coastal systems and rich ecosystems that can support the local species and meet human needs and services. The activities consist of better judgments about the regulation and protection of the use of ecosystem services, as well as enhanced efforts designed to minimize negative impacts and the magnitude of changes, such as the overexploitation of ecosystems. Information of the systems and the changes inside are crucial for managing coastal zones, as is the transfer of this knowledge to decision makers.

2. REMOTE SENSING AND WATER QUALITY ASSESSMENT

Today, several directives linked to European Union are existing which work toward the goal of ensuring the ecological integrity of Europe's waterways via effective management. However, most of statistical analysis and outputs have been based on in-situ measurements. The network from which these metrics derived have approximately 13000 sites across Europe, the number may seem high but it cannot cover all the different coastal environments of Europe. Although in-situ measurement may offer high accuracies, it is a time-consuming process, and hence it is not feasible to provide a simultaneous water quality metrics on a regional scale[12]. Moreover, conventional sampling methods are not easily able to identify the spatial or temporal variations in water quality which is vital for comprehensive assessment and management of waterbodies[13]. For example, in situ sampling has the advantage of measuring with high accuracy Chlorophyll-a but is limited regarding the spatial and temporal coverage. Chlorophyll-a concentration is recorded as little as 3 – 20 times per year in coastal waterbodies, with sampling frequencies varying widely between member states (Figure 2). Such sparse information will likely fail to accurately represent the dynamic nature of many waterbodies.

Therefore, these difficulties of successive and integrated sampling become a significant obstacle to the monitoring and management of water quality. Remote sensing, for monitoring coastal waters, have given a new perspective and important understanding of the global systems and the dynamics within. For coastal observations high-resolution sensors are needed. Using them, it is feasible to analyze the impact of transports of dissolved and suspended matter from both terrestrial run-off and river inputs on water clarity and surface chlorophyll-a concentrations in coastal zones using remote sensing and bio-optical data.

With the evolution of space science and the increasing use of computer applications, earth observation techniques have become useful tools in achieving water monitoring. Earth observation derived metrics can help fill the gaps that were previously mentioned. It can also improve the understanding of temporal and spatial variability of several quality elements within water and above the sediment surface in intertidal and shallow areas help define environmental reference status of some quality elements using historical satellite data and also provide a harmonized approach for monitoring water quality across Member States with a cost efficiency approach. Generally, Remote Sensing is the gathering of data without direct physical interaction with the assessed objects, regions, or phenomena[14]. Sensors on satellites and airplanes collect data remotely by detecting and measuring electromagnetic energy reflected off the earth's surface characteristics[15]. These features have unique spectral characteristics because the structure, physics, and chemistry of the observed surface affect the spectrum of the reflected radiant energy. Radiant energy's qualities rely on parameters such as its intensity, wavelength, and angle of incidence[16]. Optical remote sensing systems are split into two categories: multispectral systems, which detect and record between one and approximately ten spectral channels, and hyperspectral systems, which detect and record between tens and hundreds of spectral channels.

Recent studies have reported that remote sensing methods may provide comprehensive views of vast aquatic habitats. In addition to sampling, remote sensing provides a cost-effective alternative for monitoring changes in aquatic habitats. On the basis of the link between water's optical qualities and electromagnetic radiation, water quality may be determined using remote sensing[14]. Due to the fact that the backscattering properties of water are affected by the types and concentrations of components, electromagnetic radiation may be used to evaluate surface water quality[17]. Thus, a body of water's radiative upwelling may be utilized to detect the existence of water elements and measure their concentration. One of the advantages of employing remote sensing in assessing water quality is the ability to cover vast areas of water bodies spatially. In addition, the repeated gathering of remotely sensed data permits the periodic monitoring of water quality and the identification of trends. In addition, remote sensing is typically a cost-effective alternative to in-situ measurements since it does not need extensive field sampling. Consequently, remote sensing techniques have been implemented in a variety of water quality applications[18].

Specifically, Earth Observation has contributed massively to the monitoring of coastal zones and provided estimates of alteration in coastal ecosystems. Given the advances in the design of sensors and data analysis techniques, remote sensing has been capable to evaluate the quality of waters in coastal environments. Multispectral and hyperspectral sensors are used to monitor coastal water dissolved substances, and biotic/abiotic suspended particle concentrations. Remote sensing sensors can vary from aircraft of low and medium altitudes to satellites in space, depending on the requirements of resolution and cost limitations[19]. Many research studies have used satellite imagery in their methodology to obtain robust correlations between the waters' spectral value and physical and biogeochemical constituents, such as transparency, chlorophyll concentration[20].

Recent advances in sensor technology have led to the development of hyperspectral sensors (also known as imaging spectrometers) capable of collecting imagery containing several hundred bands over the electromagnetic spectrum. The concept of hyperspectral remote sensing began in the mid-1980s and has been used most widely by geologists for identification and mapping of minerals. Spectroscopy can be used to detect individual absorption features due to specific chemical bonds in a solid, liquid, or gas. Today, these sensors greatly expand the potential of remote sensing to assess, map, and monitor the characteristics of all natural resources including marine coastal zones. Hyperspectral data are particularly useful in marine coastal zones because of the spectral complexity of suspended as well as benthic features found in these environments. The very high spectral resolution of hyperspectral sensors gives them the advantage over multispectral sensors in facilitating exceptional differentiation of objects based on their spectral response in the narrow bands. The application of hyperspectral remote sensing techniques to water resource problems is proving to be the most in-depth way of examining spatial, spectral, and temporal variations to derive more accurate estimates of information required for water resource applications[21]. The most commonly used hyperspectral sensors currently in space can be found in the following table :

Type of sensor	Number of Bands	Spectral range(µm)	Resolution (m)	Imaging Swath
AVIRIS	224	0.40-2.50	17	12 km and 614 pixels per scanline
HYDICE	210	0.40-2.50	0.8 to 4	270 m at the lowest altitude
HyMap	128	0.40-2.50	3 to 10	512 pixels
APEX	Up to 300 VIS/NIR (114), SWIR (199)	VIS/NIR (0.38-0.97), SWIR1 (0.97–2.50)	2 to 5	2.5–5 km
CASI-1500	Up to 228	0.40-1.00	0.5 to 3	512 pixels per scanline
EPS-H	VIS/NIR (76), SWIR1 (32), SWIR2 (32), TIR (12)	VIS/NIR (0.43-1.05), SWIR1 (1.50–1.80), SWIR2 (2.00–2.50), TIR (8–12.50)	Dependent upon flight (min 1 m)	89 o
DAIS 7915	VIS/NIR (32), SWIR1 (8), SWIR2 (32), MIR (1), TIR (12)	VIS/NIR (0.43-1.05), SWIR1 (1.50–1.80), SWIR2 (2.00–2.50), MIR (3.00–5.00), TIR (8.70–12.30)	3 to 20 depending on altitude	512 pixels per scanline
AISA	Up to 228	0.43-0.90	1	364 pixels per scanline
HySpex ODIN-1024	VIS/NIR1 (128), VIS/NIR2 (160), SWIR1 (160), SWIR2(256)	0.40-2.50	0.5 m at 2000 m altitude	500 m

Table 1. Specification of the most commonly used Hyperspectral sensors in water quality assessment.

The process of assessing the chemical, physical, and biological features of waterbodies and identifying potential pollution sources that decrease water quality is known as water quality study. It is possible for waste discharges, pesticides, heavy metals, minerals, bacteria, and sediments to degrade water quality. Diverse water quality standards have been devised to help in determining the level of water contamination and, subsequently, to uphold these requirements. For the present study, we have concentrated over most common parameters to be monitored for water quality assessment: Chlorophyll-a, Total Suspended Matter (TSM), Turbidity and Water transparency.

3. MAIN DRIVERS AND CHALLENGES

Up to know, the missions mentioned previously have provided important benefit to scientific community to assess and model different parameters in order to derive water quality from satellite remote sensing data. However, for a commercial service adapted to the monitoring of man-linked activities such as aquaculture, fisheries, coastal tourism, harbors, there is a strong need of additional data in order to provide an efficient service. In particular the main drivers for complementary data are:

- A Ground Sampling Distance (GSD) and Global Coverage (SWATH) more adapted to the human-based activities, able to provide sufficient resolution one hand, but not too resolved on the other hand which would make more complex the process of downscaling other satellite data: in the range of 10 to 20m GSD and 50 to 100km SWATH
- A high revisit time of minimum one/day to get daily data surveillance
- A high Dynamic range and sufficient SNR on the overall spectrum for the instrument to cope for the small-scale phenomenon to be observed
- A cost-efficient remote sensing instrument in order to allow proper commercial operation and sufficient market perspectives

Additionally, it is important to take into account that most end-users are new to this kind of technics and therefore the final service will need to be user friendly, enabling both economical actors, regional and public stakeholders and potentially the general public to derive easily the main information needed. In addition, this service could also in a second time be extended to inland water monitoring, which would extend the benefit to more population and ecosystems.

At the moment, no such a service exists. The closest services existing are either the Copernicus Marine Environment Monitoring Service (CMES), Rheticus™ Marine[22], developed by Planetek, or the WaterMonitor[23] application developed by VITO. However, none of them are able to provide the necessary information for the above-mentioned applications, either because of insufficient Ground resolution, strong dependance to 3rd party microwave missions or in situ data, or limited zone coverage.

To fill this observational gap, the consortium composed of SAT4SPACE (France), Planetek Hellas (Greece), and Microelectronica SAS (Romania) has teamed together in order to propose a specific mission called ENTRUST. Its aim is to provide the necessary system to allow to monitor and control European coastal water quality and alert users of these areas with a local/ regional scale with high revisit time. This mission, in its feasibility assessment stage, is complementary to the Copernicus satellite data, and would enable to take benefit from the 2 worlds: high end and very performing missions like the Sentinels, complemented by lower and smaller missions or systems, to provide very practical services to European end users. For this mission, two different kinds of systems were traded: drones on one hand, and nanosatellites on the other hand. The main first level specifications for the hyperspectral instrument are summarized in the table below (Table 2). The paradigm shift in this study is the switch from a very wide mission definition as it is performed usually for conventional scientific satellites, to a more narrow and focused mission, which allows the relaxation of a lot of constraints at instrument level, as well as a more agile and low-cost setup, which is highly desirable for the application.

Type of Specification	Instrument Specification	Unit
Ground Sampling Distance	10 - 20	m
Swath	50x50	km
Revisit Time	1 to 2 days minimum	days
Spectral Range	430-865	nm
Number of bands	37-54	N/A
Resolution on each band	11-16	nm
Mean SNR	50-100	
Radiometric Resolution (Bit Depth)	12	bit
Mass	5 maximum	kg
Volume	20x20x20 maximum	cmxcmxcm
Power	15 maximum	W
Plateform	Drone or Cubesat compatibility	

Table 2. Preliminary main parameters for the overall hyperspectral payload

4. CAMERA AND MISSION CONSTRAINTS

At camera level, the main differences between the different hyperspectral cameras' configuration relies on the following parameters:

1) Type of acquisition: push-broom versus whisk-broom versus snapshot like type of operation. In push broom of whiskbroom mode, the detection is made on a linear detector, and the motion of an element enables the wavelength dispersion (usually a prism or a grating, or the spacecraft movement in itself). On the other hand, "snapshot like" operation exploits a 2D array with filters enabling the spectral differentiation. The filter can be either placed in front of the detector or directly integrated onto the detector itself. Both cases require less volume for the complete instrument compared to dispersive element spectrometry, but in the meantime requires important design considerations prior to the mission launch.

2) Type of dispersive element

   Mainly two types of wavelength retrieval techniques can be used: either a dispersive element, which can be mainly a prism (PRISMA mission case[24]) or a grating (OLCI case[25]), or a filter technic approach, in that case the filter lies either in front of the detector (stripe filters such as Sentinel 2 case[26]) or directly deposited onto the detector (CHIEM case with linear variable filters directly deposited onto the detector[27]). Various technics derived from this technic are nowadays being developed, combining filter technologies with image processing capabilities.

3) Type of detector technology

   The number of pixels of the detector, its pixel size, as well as is global SNR performances, depending greatly on the wavelength range covered, has an important influence on both SNR features of the final application. The pixel size and pixel pitch directly relate to the Ground Sampling Distance and the SWATH of the instrument. This is why in some case several channels covering several wavebands are selected, having a drawback on the complexity of the instrument (channels, co-registration questions) as well as the mass, volume and power consumption. In most of current missions, the main waveband covers at least the VNIR band, this being the cheapest and most important database in terms of spectrum analysis. The detector is most of the time a CMOS Silicon detector, the technology being nowadays easily available and as features such as windowing capabilities or snapshot operation which are very suitable for this type of operation, compared to CCD. SWIR and bands above in the Infra-Red are more expensive and more complex to implement, as the camera needs special design features this being either cooling requirements for the detector or specific shielded thermal design to enable proper measurement. This is why most of camera manufacturers for drones are targeting primarily the VNIR band.

At system level, being given the main requirements listed in table 2, one of the most constraintfull trade-off to be made is the type of platform to be used, the most adapted to the service needs. Indeed, the choice of the platform has important constraints on the type of Hardware (camera choice, detector choice etc.) to be selected, and needs to be chosen as early as possible.

Two types of platforms are considered for the ENTRUST project, because they answer to the need of regularity of measurements to be performed for the service: drones on one hand, cubesat on the other hand.

<u>Drones considerations and operational constraints</u>

Drones were developed starting from the early 20th century for military purposes. Known also as “Unmanned Aerial Vehicle” (UAV) they enable to remotely have operations in difficultly accessible or dangerous zones, without human intervention. Progressively, they have been transferred to civilian world, being used now for lots of purposes, from aerial photography, product deliveries, agriculture, science, leisure etc. Hyperspectral systems developments compatible with drones are relatively recent, and started in the late 2000. Most of systems were initially developed in the fields of agriculture, forestry, and mining[28]. Due to the recent and important development of this technique, a lot of systems are existing which are compatible with drones[28]. Most of the companies providing these instruments are from the US. All these cameras have different performances, wavelength range, resolution, as well as spatial resolution; for ENTRUST, the idea with this solution is to provide a low cost, easily operable system: no launch, few or even no authorization nor very specific competences to be operated. High altitude drones (eg 5-10km altitude range) are discarded since they tend to be high cost, difficult to operate and tend to be comparable in that sense with nanosatellites, with the drawback of needing a very qualified operator systematically present for operation. ENTRUST has concentrated mainly on the solution of low altitude (50-100m- commercially available) and low cost drones maximum few k€ such as Freefly plateforms or Nordic Unmanned UAVs.

The main constraints for the payload in case of drones choice are :

- Volume: as small as possible : typical: 20cmx20cmx20cm
- Mass: as small as possible : range 1 to 5 kg, varies from one drone to another and impacts the flight time)
- Operational flight time: 15min to 50min (depends on payload weight). Depending on operation, to cover a full field, several drones need to be used
- Cost of the total system (plateform + instrument): Max around 10k€-20k€, to be paid by the end user. Operator cost to be added.
- Cost of the camera: lower cost as possible, to be in line with the business model associated, eg price max around the platform cost, few k€
- Operational model: End User operated for image retrieval or service to be put in place in local EU: network of operators to be developed

<u>Nanosatellites considerations and operational constraints</u>

Nanosatellites development has increased dramatically in the early 21st century thanks to the rapid evolution and commercial development of the space industry together with electronic miniaturization. Most are placed in Low Earth Orbit and enable various operational work from science, student work up to commercial service developments in various fields (telecommunications, Earth Observation and alert purposes etc.). Beside the low cost advantage of such a solution, one of the important asset of nanosatellites is the possibility, for a relatively low cost compared to standard mission, to get high revisit time thanks to the use of constellation strategies (ex. RapidEye constellation covering the total Earth with a 3.5 hours revisit time instead of 1 or 2 days revisit time for standard satellites[29]). Several nanosatellites commercial developers and manufacturers includes: Endurosat, Gomspace, Nanoavionics, Nanospace, Surrey Satellite Technology, NovaWurks, Dauria aeropsapce etc. and this field tends to develop more and more.

In Europe, several missions have been encompassing Hyperspectral instruments[30], however, none are compatible with the aforementioned needs. Regular missions are too heavy and expensive, with most of the time insufficient revisit time.

For ENTRUST, the idea behind this solution, compared to the previous one, is to be closest to the service already developed by Planetek, Rheticus Marine, by exploiting similar source of data. The advantages being that once the satellite is launched it requires few maintenances and operation compared to drone usage (no need for an operator on the site). The drawback being the higher cost, with typical costs ranging from few hundred of k€ for students like grades nanosats, not adapted to the current commercial need in terms of performances and reliability, up to a few M€ total cost for manufacturing and launch, for regular nanosatellite mission.

The main constraints in case of nanosatellite choice are:

- Mass: 5 to 20kg acceptable depending on the platform
- Volume: to be minimized, depends also strongly on the platform. 3U to 6U maximum to minimize cost and enable a constellation strategy
- Cost of the mission: maximum 1M€, to be minimized
- Cost of the camera: maximum 1/10th of the total budget can be acceptable; the minimization of this cost enables the minimization of the complete mission coast which will raise the acceptability of this solution with respect to the market
- Operational model: Two options: Option 1: totally private mission; end user buys the mission and operation and data analysis and support is provided by Planetek for the end user, as a supplementary service. In case of non specialist end user (ex. Fishery association), the operation of the satellite needs to be provided by a third party; Option 2 : development of Planetek competences', who takes the role of service provider and satellite operator
- Mission duration: as long as possible. Typical Cubesat missions are nowadays quite short time, typically a couple of years, and one of the challenges would be to increase as much as possible the mission duration, to decrease the total cost of the mission for the service to be economically viable. Increase to mission lifetime >4years is the target

Trade off discussion

Based on preliminary service specifications (Table2), the Ground Sampling Distance (GSD) together with the SWATH are the first main parameters to be taken into account. Both have impacts on the possibility to downstream the Copernicus data, as well as importance on the overall coverage linked to the targeted applications.

By taking into consideration, performances, ease of operation the table 3 below summarizes main advantages and disadvantages of each solution.

According to this table, the nanosatellite solution is more compatible with the current service needs, both because of simpler operational model, as well as because of GSD compatibility. Indeed, the typical GSD with drones is in the cm range, which changes drastically the data retrieval strategy and in particular limits strongly the synergy with the Copernicus system, for the time being.

Therefore, ENTRUST will concentrate on the nanosatellite case, with the aim of finding as much as possible strategies to minimize the mission price, this being by hardware price strategies (NewSpace and COTS components use) or by finding acceptable solutions for end users to share common prices.

	Drone case	**Nanosatellite case**
Mass available for Payload	1 to 5kg	5 to 20kg
Volume available for Payload	20x20x20cm maximum	Adjustable depending on plateform-
Total targeted Cost	10-20k€	<1M€
Operational model	Operator needed on terrain for each measurement	Operatorless once launched
Mission Duration	As long as needed (easily duplicable)	2 years-typical
Technical Performances for the service	GSD (cm range) : not compatible with downstream need	GSD compatible (m range)

Table 3. Trade off table drones versus nanosatellite. With respect to the current application needs, nanosatellite is recommended

Nanosatellite Instrument Feasibility

Several aspects were checked in order to assess more in details the constraints at camera level. In particular a first simplified radiometric model has been implemented in order to derive important camera parameters such as:

- Camera focal length
- Number of pixels across track
- Type of detector
- Full Well Capacitance of the detector
- Typical integration time scenario

This first evaluation has been done with some assumptions that will most probably be refined in a demonstrator phase, in particular regarding:

- The 600km orbit,
- The hypothesis on maximum/minimum radiances values, taken from Sentinel 2; while the mission could most probably restrict this range due to the restriction of observation over coastal areas and/or restrict the observational range and thus relax the constraints on the camera level.

Based on these assumptions, the following preliminary parameters have been derived (Table 4), in order to allow the scan of the market in terms of available cameras:

Parameter	**Unit**	**Value**		
Flight Altitude	m	600000		
GSD accross track	m	16		
SWATH	km	68		
Aperture diameter	m	1,00E-01		
Entrance pupil area	m2	0,007853982		
Pixel view solid angle	sr	7,5625E-10		
Instrument optics mean transmission (including gratings or filter T)	N/A	60%		
Camera focal length	cm	20		
Pixel pitch	µm	5,5		
Detector number of pixels X (accross track)	N/A	4096		
Detector number of Pixels Y (Wavelegnht)	N/A	1000		
Detector Quantum Efficiency	N/A	50%		
Detector Integration time	s	0,005		
ADC converter	bits	12		
Signal level due to the Scene		**L Mini**	**Lref**	**L Max**
Typical Scene radiances, ToA	W.m-2µm-1sr-1	1	90	615,5
Wavelength	nm	865	444	490
Spectral resolution	µm	0,011	0,011	0,011
Photon Energy at wavelength	J	2,29595E-19	4,47297E-19	4,05306E-19
Number of electrons created on the spectral bandwidth	e-	4,27E+02	1,97E+04	1,49E+05
		Big capacitance	Small Capacitance	
Full Well Capacitance (FWC) needed	e-	1,64E+05	2,85E+04	
%FWC in ideal case (big capacitance)	%	0,26%	12%	91%
%FWC in ideal case (small capacitance)	%	1,50%	69%	523%

Table 4. First iteration of camera parameters. The radiance range can be covered with a single capacitance, however the linearity range for the detector as well as SNR will be strongly degraded in Low Flux cases; the best option is to have a second “small” Full Well Capacitance of about 1 order of magnitude below.

The radiances values can be almost appropriately covered with one Full Well Capacitance of about 160ke-, and one reasonable integration time of 5ms, however, to enable proper measurements and spectrum comparison, in particular at low radiances, it is recommended to use either 2 integration times or 2 full well capacitances. The solution with 2 Full Well Capacitances is preferred for reasons linked to calibration: the best option would be 160ke- and 30ke-.

Three manufacturers were identified as best option for this application; they were selected on the criteria of:

- the industrial capacity of the partner in order to enable regular commercial delivery of satellites

- the information available on the closest performances to the requirements

From these 3 manufacturers, the camera performances were more deeply investigated and compared to the specification needed; Unfortunately, only little technical information is available from Dragonfly aerospace, beside several contact attempts to get more information. The table below compares the available information.

	Requirement	**Simera Sense** **Hyperscape 100**	**Cosine** **Hyperscout-S**	**Dragon Fly** **Chameleon-HS**
SWATH (km)	68 (equivalent to 57km@500km)	19,4 @500km	115 @500 km	20
GSD (m)	17 (equivalent to 14m@500km)	4,75@500km	28 @500km	20
Orbit	600km	N/A(mission dependant)	N/A(mission dependant)	N/A (mission dependant)
Camera focal lenght (cm)	20	58	10	Not disclosed
Aperture diameter (entrance pupil) (m)	1,00E-01	0,095	0,025	Not disclosed
total optics mean transmission (including filters/ dispersive element)	60%	Not disclosed	Not disclosed	Not disclosed
Pixel pitch (µm)	5,5	5,5	5,5	Not disclosed
Number of pixels (accross track)	4096	4096	4096	Not disclosed
Numer of pixels (along track)	1000	Not disclosed	Not disclosed	Not disclosed
Spectral Range (nm)	400-860	442-884 (Option 4)	450-950	Not disclosed
Numer of bands	54	32	50 nominal (up to 120)	148
Bandwidth resolution (nm)	0,011	0,019	0,016	Not disclosed
Detector Quantum efficiency	50%	Not disclosed	Not disclosed	Not disclosed
Full Well Capacitance : Big Capacitance (High Flux) (e-)	164000	13500	13500	Not disclosed
Full Well Capacitance : Small Capacitance (Low Flux) (e-)	28000	NA	NA	Not disclosed

ADC converter (bits)	12	12	12	8 or 16
SNR	100 over all bands	15 to 80	50 to 100	Not disclosed
Type of detector	CMOS	CMOS Global Shutter	CMOS	Not disclosed
Dimensions	3U to 6U cubesat compatible	98x98x176mm	1,6U	10x10x21.5 cm
Type of dispersive element camera	LVF preferred	Not disclosed	LVF	Not disclosed
Mass (kg)	1,5	1,1	1,3	1,6
Data transfer and processing	as much as possible Processing on board	Not disclosed	L0 to L2A available on board	Not disclosed
Power consumption (W)	10	7	9	10
Space heritage	TBD	TID up to 15krad	Partially (TBC)	TID 30krad

Table 5 : Comparison of 3 off the shelves hyperspectral cameras, at 3 different manufacturers. Cosine is the closest to the requirements for the ENTRUST mission. Note that Media Lario (Streego) has also been considered in a first instance but disregarded as the proposed camera is too heavy and thus does not ensure high compatibility with nanosat constraints.

From the table, the following conclusions can be drawn:

- the closest camera for ENTRUST mission is the Hyperscout-S from Cosine, being the closest in terms of GSD and SWATH, SNR and bandwidth; as well as encompassing onboard processing
- However, the use of a very small Full Well Capacitance (13,5ke-) does not enable to cover the full dynamic range with a single integration time, and implies a very small integration time for the high flux range which feasibility will have to be checked; Note that the same detector is used by most of hyperspectral camera manufacturers, which shows a room for improvement for market needs
- The price of the camera still needs to be refined and discussed with the suppliers as most of them are above the 100k€ limit price set for the mission in order to allow a constellation strategy, in a Low cost-Newspace model. This will have to be refined in a future phase

To deal with the technical limitations linked to the detector FWC in particular, a second option has been studied: the use of a specific detector as close as possible to the requirements, to be integrated in either an existing of custom camera in link with the application. The main parameter investigated in this respect is the Full Well Capacitance requirement that would enable to cope with the large Dynamic Range.

We have investigated the following possibilities with two very different strategies in mind:

- Pyxalis with its GIGAPYX detector, tailored for space use, with a rad hard design
- G-Pixel with its GSENS400 BSI, scientific grade detector not space qualified but closest to our need on the market

Investigation is currently on-going with e2V with a potential supplementary alternative.

The 2 possibilities offer a wider dynamic range. The table below (table 6) compares the different possibilities with the requirements at service level.

	Requirement	**Pyxalis- GigaPix**	**G-Pixel-GSENS400BSI**
SWATH (km) @600km Orbit	68	109	67
GSD (m) @600km Orbit	17	13	33
Pixel pitch	5,5	4,4	11
Number of pixels (accross track)	4096	8320	2048
Numer of pixels (along track)	1000	5465	2048
Spectral Range (nm)	400-860	350- 950nm	300-900nm
Numer of bands	54	TBD (LVF- feasible)	TBD - LVF to be discussed
Bandwidth resolution	0,011	TBD	TBD
Detector Quantum efficiency	50%	>50% on [450-650] / 25% [650-850]	>50% [350-850nm]
Full Well Capacitance : Big Capacitance (High Flux)	164000	50000	90000
Full Well Capacitance : Small Capacitance (Low Flux)	28000	5000	NA
ADC converter (bits)	12	12	
SNR	100 over all bands	TBD	TBD
Type of detector	CMOS	CMOS Rolling Shutter	CMOS Rolling Shutter
Power consumption	10W	<6W (without cooling)	3,5W (without cooling)
Space heritage		RadHard Design	No heritage, Scientific grade detector, to be qualified

Table 6 : Detectors customization options. Pyxalis is the closest to the current need, with improved FWC and dual FWC possibilities which matches the mission scenario needs (see Table 4).

Pyxalis GigaPyx is the closest to our requirements, both in terms of Higher Dynamic range, as well as multiple capacitance and low noise; in addition, the manufacturer has already worked on the possible integration of Linear Variable Filters suitable for the application, which is a plus. However, at the moment, no hyperspectral camera incorporates such detector which means that either a camera should be specifically developed or a discussion should be started with current hyperspectral camera manufacturers to evaluate whether the detector can be integrated in one of their camera, with little adaptation. Nevertheless, it confirms the importance of the detector as a Key Enabling Technology for such application, and the possibility to open new markets for hyperspectral camera manufacturers for similar applications.

5. CONCLUSION AND PERSPECTIVES

In conclusion, different system hypothesis were investigated in order to match the needs of water quality service feasibility. In summary, it was shown that:

- the hardware related to a water quality monitoring service is feasible
- A nanosatellite solution is more adapted than a drone solution in the short term for the application

- Three cameras off the shelves have been identified, with Cosine Hypercout-S being the closest to the requirements, with however a question mark on the High Dynamic Range needed to accommodate the full flux
- A better solution with respect to technical feasibility would be to integrate the Pyxalis GIGAPYX 4600, which, in the case of a specific camera integration, would match most of the requirements to be compatible with the water quality monitoring application; however, a custom or tailored camera would have to be manufactured, and the question remains about the targeted price range

From a market perspective, it is important to highlight that the use of nanosatellites today is primarily for large companies that may afford paying this service; to enable a wider spread of this technology three possibilities were identified, such as:

- using and sharing an existing nanosatellite together with others, that is less costs, but waiting for a common launching and sharing the data that the nanosatellite camera is providing with possible limitation on performances; Synergy could be looked at from a Scientific perspective
- launching a specific nanosatellite for the service, by teaming with a specific nanosatellite operator; the cost would be higher however, the nano satellite may be equipped with the necessary camera; precise business model has to be refined

Concerning drones, their use can still be interesting for local/regional, small companies that need a random service, or a regulate one, fully decided by its own management. Nevertheless, there is still technical work to be endorsed to see how to maintain high performances in water quality retrieval, specially at data treatment level.

The next step for the ENTRUST project is to go towards practical demonstration, to validate not only the hardware configuration, but also to validate the data treatment scheme, that was not exposed within this paper. This demonstration would enable not only to be at the forefront of water quality management and monitoring for Europe, with innovative technologies and services, but could also be a first step to define better what type of information would be more relevant in the frame of the future upcoming missions such as the Copernicus future Sentinels.

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