Compact Hyperspectrals

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ABSTRACT

Numerous Hyperspectral Imagers have been launched or are being built for resource management, monitoring anthropogenic effects on the troposphere gases, and for defense applications. Payloads such as Hyperion, EnMAP, HyspIRI, and SCHYAMACHY are instruments with mass in excess of 100 Kg. Technologies recently developed in precision manufacturing of aspherical mirrors, detectors, and spectral filters allow to shrink a hyperspectral instrument in an envelope that will fit on a small satellite, or even in a CubeSat.

The reduction of mass, volume, and power is not the only problems to be solved to successfully use a hyperspectral on board of a small satellite. The amount of data acquired over one orbit can be as high as 1 TB (terabyte). To store and download the data can be unmanageable tasks for the resources of a small satellite. The reduced mass and volume of a compact hyperspectral comes at the expenses of a decreased signal to noise ratio. Can digital image processing and the knowledge acquired with the hyperspectral already in orbit help to compress the data to a manageable size? What type of information can be extracted from a compact hyperspectral?

The paper describes the results obtained with the PhytoMapper, a technology demonstrator of a Compact Hyperspectral Instrument recently developed. The instrument fits in a volume of approximately 15 cm³ (6 cubic inches) and has a mass of approximately 2 Kg. The instrument has a spectral resolution of 10nm, a field of view 34 degrees, and 2400 spectral bands. If flown on a 600km polar orbit, it will provide 100m spatial resolution and 3 days revisit time. The work presents the performance measured in the lab and the analyses performed to assess what type of mission objectives are achievable with this instrument. Further work has been done to push the envelope of a Hyperspectral within a CubeSat. A micro-telescope with a very aggressive optical design has been built and tested. The paper gives an overview of the performance that can be achieved with this extreme downscaled hyperspectral instrument and what, in the view of the Authors, can be the possible applications. A roadmap from the current technology status to the in-flight demonstration is finally presented.
INTRODUCTION

The spectral components of the light emitted or reflected by an object contain a variety of information that may be used to understand the chemical composition of the observed scene. This is the basis of remote sensing. The spectral analysis of light is used to monitor the Earth environment, the effects of anthropogenic activities, or to study Planets and Stars atmosphere. Each substance, chemical or physical process has its own spectral signature from which an observer can gain a wealth of information. The analysis of the spectral signatures of the observed scene is a complex matter. Development of instruments and methodologies to retrieve quantitative information has been a subject of work since the early days of spectro-radiometry.

Remote Sensing technologies and retrieval algorithms have progressed hand in hand and have significantly improved the capabilities to quantitatively measure the chemical compositions and the chemical processes of the observed scene.

The instrument to quantitatively measure the spectral radiance is called spectro-radiometer. A spectro-radiometer can either analyze the source in a limited number of spectral bands ( multispectral spectro-radiometer) or a in the continuum of a spectral interval. The latter is called Hyperspectral. A Hyperspectral Instrument is generally composed of a telescope focusing the light coming from the observed scene on an entrance slit; the light is then dispersed in its spectral components by a grating or a prism and focused on a detector (Figure 1). The signal generated by each spectral component is only a fraction of the total incoming light; therefore the telescope of a Hyperspectral may be very bulky to collect enough light to achieve an acceptable signal for each spectral component. Furthermore, the limitations of manufacturability of the optical components of both the telescope and spectrograph limited the field of view or the resolution of the hyperspectral manufactured until recently.

New optical manufacturing technologies, the development of new optical filters and large area CMOS detectors opened the door to the development of hyperspectral instrument of very compact size and with good spatial resolution. Spectral resolution and Signal to Noise Ratio are limiting factors of these types of compact hyperspectral, but they can be used to perform meaningful operations thanks to a deeper understanding of the retrieval algorithms.

MINIATURIZATION TECHNOLOGIES

A numbers of new technologies concurred in making possible to build a compact hyperspectral:

- Optics Fabrication: the development of lathe accurate at nanometer scale;
- Materials: Aluminum alloys obtained with a rapid solidification process to manufacture mirrors;
- Metrology: Non contact measurements for optical metrology of aspherical surfaces and 3D contact measurements used for alignment;
- Optical Filters: Linear variable filter to separate the spectral components;
- Detectors: Large area CMOS detector in the visible range and uncooled InGaAs detectors for the short wave infrared;
- Electronics: ICs for the readout circuitry of the detectors, and high speed memory and data processing for acquisition and storage of data.

To describe in detail each of the above technology developments is beyond the scope of this paper. Nevertheless, it is relevant to provide to the Small Satellite community an overview on how recent advancements makes possible to build a compact hyperspectral that is disruptive with respect to the hyperspectral instruments currently available.
Optics Fabrication, Materials and Metrology

The production of well controlled aluminum alloys obtained with the Rapid Solidification Process recently developed by RSP Technologies provides alloys with its components, as Magnesium, highly dissolved in the aluminum bulk. This alloy, developed for manufacturing Pistons for high performance cars, revealed to be a very good material for production of mirrors for telescopes. The thin structure of the alloy gives the possibility to manufacture optical mirrors with modern Single Point Diamond Turning lathe. The surface finish of this production method gives surface roughness routinely below 6 nm. Roughness as good as 1.1 nm has been reached under special conditions. A mirror manufactured with surface roughness of only a few nanometers does not need the costly post polish process. The cost saving and flexibility obtained with the combination of the Aluminum alloys with the Single Point Diamond Turning provides a huge leap in optical fabrication. Manufacturing of mirrors with accurate computer controlled lathe without the need of polishing gives the possibility to virtually manufacture any shape opening the possibility to design optical systems with very complex aspherical surfaces, unthinkable until recently. The difficulty of assembly and verification of an aspherical optical system has been solved by modern metrology. The freedom of selecting any high order aspherical for the optical design provides the possibility to design a very compact reflective telescope with high optical quality and wide field of view. Within the last couple of years Proba-V and Tropomi took advantages of these developments. Both instruments use mirrors with high aspherical shapes that could not be manufactured with conventional methods. These solutions are significantly more compact and have a resolution one order of magnitude better than previous designs.

Optical Filters

The complex optical systems of a spectrograph can be replaced by one single element: the Linear Variable Filters (LVF). This optical device is a set of interference filters with variable thickness accurately deposited on a substrate (glass of quartz). The transmission bandwidth of such a filter is constant along the uniform direction of the coating and varies in the orthogonal direction. By placing the LVF in front of an area detector, a system is obtained where each detector row collects the light corresponding to spectral band transmitted by the portion of the filter in front of it. An entire spectrograph can be replaced by just one element: the Linear Variable Filter. This solution, even if it is conceptually simple, requires a very complex manufacturing process. Dozens of layers need to be accurately deposited next to each other. Only recently, the control of the deposition of these layers has reached the accuracy to obtain a manufacturing process with non-zero yield. Figure 2 shows the configuration of the compact hyperspectral. The entire spectrograph is now replaced by one component: the linear variable filter.

Detectors and Electronics

Detectors and electronics follow from the rapid evolution of the consumer electronics, as mobile phones, digital cameras and computers. So there is no surprise that detectors in the visible range and its associated read-out electronics have constantly increased their performance and lowered the power consumption. In particular, a significant improvement has been achieved using CMOS detectors instead of CCDs. Furthermore, one development not yet of large use in consumer electronics deserves some attention: InGaAs detectors able to operate in the short wave infrared (SWIR) without cooling. Space borne optical instruments working in the SWIR have been using HgCdTe detectors needing a massive, expensive and power hungry cooling systems. InGaAs detectors are still limited in terms of detector format and wavelength bands, but are in rapid development. With the current technology it is possible to build a SWIR system with a cut-off wavelength up to 2.3µm, but still with a small format. It is expected that the market applications of these devices to both Space and ground based surveillance will pull the companies to develop larger and more performing detectors.

Figure 2

Just combining the above technologies in a smart way it is possible to build a hyperspectral instrument that is very compact and significantly cheaper with respect to what has been built so far. Nevertheless, a quick
performance analysis shows that the signal to noise ratio and the spectral resolution are depressively low when compared to existing instruments. The problems are then: is there any advantage in having a not so performing but small and cheap hyperspectral? Is there any application where a compact hyperspectral can deliver interesting measurements? As in many cases of disruptive products, initially the answer to both questions was ‘no’.

**Size and Performances**

In spite of the doubts on its potential use, it was decided to assemble and test a breadboard of a compact hyperspectral with the objectives of measuring the achievable performance with the state-of-art technologies, investigating potential applications, and defining possible evolution of this type of instrument.

A comparison of characteristics of a compact hyperspectral, reported in Table 1 shows the big advantages of the compact hyperspectral with respect to other hyperspectral instruments: low mass, and large field of view.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PhytoMapper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>90mm</td>
</tr>
<tr>
<td>F#</td>
<td>5</td>
</tr>
<tr>
<td>Field of View</td>
<td>34° x 5°</td>
</tr>
<tr>
<td>GSD at Nadir</td>
<td>48m</td>
</tr>
<tr>
<td>Spectral range (VNIR)</td>
<td>400 nm ÷ 1000 nm</td>
</tr>
<tr>
<td>Number of bands</td>
<td>2400</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>10 nm FWHM</td>
</tr>
<tr>
<td>SNR</td>
<td>50</td>
</tr>
<tr>
<td>System MTF</td>
<td>0.15 @ 91 lp/mm</td>
</tr>
</tbody>
</table>

The next question was how we could take advantage of these key assets. Two directions of work have been identified:

1. **Early detection of anomalies.** We defined “anomaly” any situation in which the spectral signature differs from the expected scenario, as for example a flood, a forest fire, oil spill, or an illegal dump. The compact hyperspectral could be used for early detection of the event and definition of the perimeters of the interested area. This information could be passed to a Hyperspectral Instrument with high performance but limited field of view. The high performing instrument could be on board of a larger satellite flying in tandem or even on the same satellite, provided that the computing time for image processing and satellite agility could be sufficient for autonomous on-board re-tasking of the observations.

2. **Cloud detection.** Measurements of high performance hyperspectral systems are highly affected by the presence of cloud. A system with a large field of view mapping the clouds distribution could improve the measurement capabilities and reduce the data rate of high performing hyperspectrals.

We focused on point 1, because the cloud detection would need SWIR/TIR sensors that are outside of the scope of the present development, but it is surely one application we will take into consideration for future evolution.

**THE PHYTOMAPPER**

The breadboard of the Compact Hyperspectral has been dubbed “PhytoMapper” to outline the intention to use the instrument to map biological activities (from Greek Phyto: plant, organism). The elements composing the PhytoMapper are a Three Mirror Anastigmat (TMA) telescope, a linear variable filter and a CMOS detector. The parameters of the PhytoMapper are reported in Table 2:
variable filter is theoretically 1% of the wavelength, but in reality 2% is already difficult to achieve; i.e. resolutions in the visible range is limited to approximately 10nm.

Furthermore, linear variable filters have poor out of band rejection limiting the capability of this instrument to resolve spectral signatures. Finally, the 2nm surface roughness of the mirrors, achievable with the best manufacturing process, generates straylight that degrades both contrast and spectral resolution.

PERFORMANCE RESULTS

The test campaign of the Phytomapper breadboard has been dedicated to acquire experimental data used in the retrieval model to understand potentialities and limitations of this configuration.

The first test activity was to characterize the capability of the LVF to resolve spectral signature. Tests were performed using Erbium as a test sample. The plot of Figure 7 shows the spectral signature of Erbium measured with a high resolution spectrometer (black solid line ASD), the convolution of the Erbium spectrum and the LVF spectral response is reported in green. The measurements done by the PhytoMapper are in grey (CHIB stands for Compact Hyperspectral Imaging Breadboard). Finally the red line reports the running average to smooth the measurement noise. The structure of three minima of the spectrum of Erbium can easily be indentified with the measurements done by the PhytoMapper. At the same time, it is clear that the structure of secondary minima in the range 525nm – 575nm can not be resolved.

These results indicated two areas of work:

- Application Analysis: to identify what types of substances can be resolved
- Post Processing: To investigate possible post processing methods to enhance the capabilities of the instrument.
APPLICATION ANALYSIS

After a survey of the requirements for various application areas, it was concluded that, due to the high number of spectral bands, wide spatial coverage but relatively modest SNR ratio and rather broad spectral bands, the main application of this type of instrument will be forestry, agriculture, land use and limnology.

Although the Phytomapper could provide valuable data for many applications, the low SNR is limiting the applications to detection of irregularities rather than a quantification of parameters.

A possible application could be the improvement the current land cover classification at higher spatial resolution. With its high number of spectral bands and frequent revisit, the PhytoMapper gives the possibility to follow the changes in biophysical variables at a large scale. The Phytomapper, as it will be shown later in this paper, will be able to detect changes in forestry related biophysical variables, such as biomass, Leaf Area Index (LAI), tree cover. As such, large forest fires and deforestation can be monitored. Also forest species classification can be improved by including phenology. On the other hand, species classification can be hampered by the low SNR.

Radiative transfer simulation study

For the analysis of applications a performance simulation of the instruments combined with a radiative transfer modelling has been performed to gain insight on how the spectral profiles measured by the PhytoMapper would look like after the light has travelled through the atmosphere. This analysis is necessary to evaluate the end to end performance of the instrument and to judge possible applications of the Phytomapper.

The simulation allowed to verify to which extent changing biophysical parameters in vegetation and water could still be monitored by the PhytoMapper. Consequently, this study enables us to, from an application point of view, better judge the impact of the instrument performance. The goal is to give a first indication for two key applications: water and vegetation.

The simulation allows to vary the concentrations of the physical parameter to be measured, e.g. the concentration of chlorophyll, to propagate the spectrum through the atmosphere and into the instrument, to apply the retrieval algorithm to quantitatively verify the capability of the PhytoMapper to measure the physical parameter. The flowchart of Figure 8 presents the methodology used in this study. Three steps can be identified: 1) the generation of spectra, 2) the instrument simulation and 3) the application analysis. The flowchart represents the simulations on water, but simulations on vegetation follow the same scheme.

![Figure 8](image_url)

The simulation process starts with the selection of the specific physical parameter to be studied in detail. We decided to use the chlorophyll (CHL) concentration in water. Hydrolight, a radiative transfer model, was used to generate water-leaving spectrum and vegetative reflectance spectra. The reflectances are converted to Top-of-Atmosphere (TOA) radiances using the Modtran radiative transfer code.

The resulting TOA spectra are then used as inputs for the instrument simulation. The instrument simulation is done by first modelling the spectral filtering of the instrument for each of the bands generated by the LVF filter, and further by modelling the signal random noise. For spectral filtering, measured data for the Quantum Efficiency of the sensor and LVF filter response have been used.

After this filtering, the registered and filtered spectrum is converted into the electrical signal, as it would be generated by the instrument. Shot noise, dark current noise and detector readout noise were added to the signal assuming a zero bias Gaussian noise. This process was done 100 times per band to simulate 100 different measurements of the same spectra by the same pixel. No viewing-dependent or pixel-dependent factors have been used in the simulation.

The instrument spectra thus generated are in values of electron signal. Now the signal can be converted back to equivalent TOA radiances by performing the inverse conversion, i.e. dividing by the normalized filter response:
\[
\frac{\int F(\lambda) I(\lambda) d\lambda}{\int F(\lambda) d\lambda}
\]

where \(F\) is the filter response and \(I\) the input spectrum.

The atmospheric correction is performed to get the instrument specific water-leaving reflectance spectra. Then physical parameter, e.g. concentrations of Chlorophyll, is estimated by applying the relevant retrieval algorithm. A separability check is performed retrieved reflectance spectra.

**Spectra Generation**

Vegetation canopy reflectance spectra were generated for leaf chlorophyll contents varying from 5 to 45 µg/cm² (Figure 9). The canopy radiative transfer model chosen in this study is ACRM and has been developed by Kuusk. It is a two-layer canopy reflectance model which simulates the directional reflectance of a homogeneous layer of vegetation and a thin layer of vegetation on the ground surface in the 400–2400 nm spectrum with a spectral resolution of 1 nm. The model accounts for the non-lambertian soil reflectance, specular reflection of direct sun radiation on leaves, hotspot effect and a two-parameter leaf angle distribution. It requires information on the spectral variability of soil reflectance as a function of four vectors according to Price², illumination conditions and a set of plant specific parameters, such as, leaf area index (LAI), leaf angle distribution (LAD), leaf size, and an accurate description of leaf optical properties.

The latter were simulated with the PROSPECT model (version 3.01) to obtain a larger variability in leaf biochemistry. PROSPECT is a simple but effective radiative transfer model that calculates the leaf transmittance and reflectance with a limited number of input parameters: the leaf internal structure parameter \(N\), the chlorophyll content \(C_{ab}\), the equivalent water thickness \(C_{w}\) (cm), and the leaf dry matter content \(C_{m}\) (g cm⁻²).

**Water-leaving reflectance**

Water-leaving reflectance was simulated using the Hydrolight radiative transfer model. Hydrolight uses as input the concentrations of the optically active constituents in the water and their optical properties. There are three optically active constituents: Chlorophyll (CHL), Total Suspended Matter (TSM) and Coloured Dissolved Organic Matter (CDOM). The CDOM concentration is represented by the absorption at 440 nm (aCDOM). Simulations were performed for aCDOM between 1.1 and 2.5 m⁻¹, CHL concentrations between 0 and 30 µg/L and TSM concentrations between 20 and 100 mg/L. (Figure 10 and Figure 11. These concentrations are representative for coastal waters and estuaries. The optical properties were taken from the Scheldt River and were measured in the laboratory from water samples collected in-situ.

![Figure 9](image_url)

![Figure 10](image_url)

![Figure 11](image_url)
Top-of-Atmosphere Radiance Spectra

Atmosphere was added using Modtran to obtain a real scene scenario. Atmospheric contribution was simulated for May 17, a platform altitude of 800 km, a visibility of 17 km, a water vapor content of 2.5 m⁻¹ and a rural aerosol (Figure 13 through 17 shows radiances at sensor for different combination of Chlorophyll (CHL), Total Suspended Mass (TSM), and Coloured Dissolved Organic Matter (CDOM).
Instrument simulation

Instrument simulations have been done for each of the input spectra, with 100 output spectra per input spectrum to have 100 different noise values calculated with a zero mean Gaussian distribution. Comparing the canopy reflectance (Figure 9) with the water-leaving reflectance results (Figure 11, Figure 12, and Figure 13), it is obvious that water-leaving reflectance spectra will suffer more from limited SNR performances. The cause of this is the lower signal in the water-leaving cases: the SNR ratio is inherently worse for a lower signal response because the associated signal noise decreases at a rate which is the square root of the signal.

Figures 18 and 19 show original and Phytomapper at-sensor radiance and canopy reflectance spectra for a leaf chlorophyll content of 5 µg/cm², not-corrected and corrected for atmosphere respectively. Figures 20 and 21 show original and Phytomapper at-sensor radiance and water-leaving reflectance spectra for a CHL concentration of 30 µg/L and a TSM concentration of 100 mg/L, not-corrected and corrected for atmosphere respectively. Finally, Figures 22 and 23 show original and Phytomapper q-sensor radiance spectra for a CDOM of 2.5 and a TSM concentrations of 100 mg/L, not-corrected and corrected for atmosphere respectively.

The simulations show very clearly the trend to underestimate the radiance at the shorter wavelengths of the spectrum and overestimate at longer wavelengths, most noticeably for the water-leaving spectra. This is the consequence of the out-of-band response of the LVF filter: since water-leaving reflectance spectra are significantly higher at the short wavelengths, an out-of-band response at longer wavelengths will give a net reduction of the response after the radiometric correction, according to Eq. (1).

Note that this conversion is optimal for the case where the filter is a square pass-band filter. In this case, the operation of filtering and converting back is equivalent to averaging the filter response. However, in the case of the LVF filter, this ‘averaging’ also includes, in lesser extent, the contribution of out-of-band regions. Hence, if these regions have an input spectrum lower than the in-band region, as is the case of shorter wavelengths, the signal will be underestimated; when these regions have an input spectrum higher than the in-band region, the inverse case happens.

Separability check on simulations

A separability check is performed on the simulated atmospherically corrected reflectances and then a retrieval test is performed after applying an algorithm to retrieve the corresponding concentrations.
For each spectrum there are now 100 simulations. From these 100 simulations the average and standard deviation is calculated per spectral band. In Figure 24 the upper plots show each time two simulated water-leaving reflectance spectra with different chlorophyll content (red and blue). The difference between these two spectra is shown in green in the plots below. The noise level (standard deviation) for the 100 simulations is superimposed. For all cases the difference curve is below the noise level beyond +/-700nm. For the second case the noise level is comparable in the visible bands which indicate that it will be impossible to discriminate between a CHL concentration of 3.33 and 6.67 µg/L. However based on case 1 and case 3 we can conclude that water with a high CHL concentration of 30 µg/L is distinguishable from water with a CHL content of 16.6 and 3.33 µg/L in the visible bands.

A similar analysis for the vegetation simulations is shown in Figure 25. Since the values of the difference curve are higher than those of the curves representing the (noise) standard deviation, we should be able to distinguish leaves with 5 and 10 µg/cm² chlorophyll, and 40 and 45µg/cm² chlorophyll in the 450-700 nm and 500-600nm respectively.
Retrieval Algorithms and Retrieval Limit

To know the retrieval limit after instrument simulation, algorithms were applied to retrieve the CHL concentration from the canopy reflectance spectra and to retrieve the SPM, CDOM and TSM concentration from the water-leaving reflectance spectra. The algorithms are applied on both initial simulations and on the atmospherically corrected spectra after instrument simulation. For the vegetation spectra a CHL index is used, for the water spectra a curve fitting technique is applied.

1. Chlorophyll indices

Chlorophyll indices are developed to maximize the sensitivity to chlorophyll content whilst minimizing sensitivity to other terms. They have proven to be very successful and helpful in terms of data processing and analyses. Many chlorophyll indices can be found in literature and the majority of them are tested in this study based on an overview found in Delalieux. As it was meant to study the potential of the novel sensor to distinguish spectral signatures of canopies having different amounts of chlorophyll, canopy spectra with nine different levels of chlorophyll concentrations were simulated (5, 10, 15, 20, 25, 30, 40 and 45µg/cm²). Only variations of chlorophyll are considered in the simulations, while all other model parameters were kept constant. For each chlorophyll concentration, 100 sensor specific simulations were made. Index values were calculated for each simulated spectrum. Only the results of the best performing indices are shown. For ratio indices, the R750/R710 (Zarco-Tejada) index is used (Figure 26 left), while for standardized indices, the (R750-R660)/(R750+R660) (Gitelson and Merzlyak, 1994) index is selected (Figure 26 right). Red dots represent the index values of the original simulated spectra as obtained by ACRM, i.e., without any noise (sensor nor atmospheric) added. The nine groups were compared by means of the non-parametrical multiple test procedures (Behrens-Fisher- and Steel-type for all-pairs and many-to-one situations).

From the Figure 26, it can be concluded that a good correlation exists between the input chlorophyll concentrations and the chlorophyll index values of the simulated spectra. Moreover, statistics have shown that all groups differ significantly (alpha=0.05). Moreover, it can be deduced that the standardized index enables a perfect distinction between spectra of different groups having low chlorophyll contents (5-20µg/cm²). For canopy spectra having chlorophyll contents of 25µg/cm² or more, it is less obvious to point out to which group they belong. From this simulation study, it becomes clear that the novel sensor, notwithstanding the low SNR, still has a lot of potential for interspecies classification and vegetation stress detection studies. It can be interpreted by which chlorophyll concentration, an optimal detection could be realized. The PhytoMapper should, for example, allow us to make a distinction between peach orchards, with a typical chlorophyll concentration around 35 µg/cm², and citrus orchards with chlorophyll contents around 55µg/cm².

However, the main problem of almost all chlorophyll related vegetation indices is their saturation at high chlorophyll levels or at low chlorophyll levels and high LAI values. This saturation level will be reached at lower chlorophyll and LAI levels with this novel sensor, probably due to poor out of band rejection of the filter.

Once again, it has to be noted that this simulation study represents an ideal case in which only chlorophyll concentrations are varied. More simulations should be done in order to conclude on the final performance of the novel sensor for this type of application studies, but this is out of scope of the current project.
2. Curve fitting

In the curve fitting procedure (Figure 28) TSM, CHL and CDOM concentrations ($\hat{c}$) are estimated by minimizing the error between modelled ($\hat{R}$) and simulated spectra. In this approach the model of Albert and Mobley$^5$ was used in the forward calculations. This model can be seen as a simplification of Hydrolight. The algorithm starts with a set of initial concentrations values for CDOM, TSM and CHL. The optimizer then calculates the RMSE between simulated ($R$) and modeled ($\hat{R}$) spectra and subsequently adjusts the input concentrations ($\hat{c}$) until a minimum RMSE is obtained.

![Figure 27](image)

Figure 27 represents the results of the curve fitting procedure in boxplots with on the x-axis the original input concentrations for the simulations and on the y-axis the estimated concentrations. Red dots represent the values of the original simulated spectra without any noise added: the figure at the left for 4 different CHL concentrations and a SPM concentration of 100 mg/L, the figure in the middle for three different CHL concentrations and a SPM concentration of 20 mg/L and the right figure for 5 different SPM concentrations. It is clear from the red dots on these figures that the curve fitting procedure works very well for the estimation of TSM but less for the estimation of CHL. When noise is added the groups with different TSM concentrations are significantly different. However this is not the case for varying CHL concentrations. In particular the lowest CHL concentrations become difficult to discriminate.

As for the analysis of the vegetation spectra, we conclude that the PhytoMapper has potential for TSM retrieval in coastal waters and even for the detection of harmful algae blooms. These algae blooms are observed as abnormal high concentrations of CHL (e.g. 90th percentile of yearly observed CHL concentrations).

Simulation conclusion

These first simulations indicate that the new instrument allows to information on the vegetation CHL content and SPM/CHL in the water. It has to be noted that these results are dependent on the type of retrieval algorithm being used and the input optical properties (in this case for the Scheldt estuary).

To make a more founded judgment on the performance of the novel instrument, much more simulations are needed and different types of algorithms should be tested. Improvements of the instrument should primarily focus on an increase of SNR performance and reduction of the spectral bandwidth.

![Figure 28](image)

PUSHING THE ENVELOPE WITHIN A CUBESAT

CubeSats attract a significant attention as being very low cost and compact platforms. A study investigating down scaling of the PhytoMapper to become a potential CubeSat payload resulted in a design of an extremely compact (60x50x30mm$^3$) TMA telescope with highly aspherical mirrors which is illustrated in Figure 29.

![Figure 29](image)

Figure 30 shows the micro-TMA optical design with different FOVs imaged on the focal plane.
The total FOV of this micro-TMA is 50 degrees, it has a focal length of 40mm and an F-number 6. The breadboard of the micro-TMA had been manufactured by VDL, in the Netherlands within the framework of ESA technical assessment program. This breadboard includes mirrors and structures. A surface roughness of 4 – 6 nm was achieved for the mirrors. The precise manufacturing capabilities of the diamond turning machine allowed alignment of the TMA by design. The parts of the telescope had been put together without any additional alignment.

The assembled micro-TMA had been optically tested at ESA/ESTEC for WFE and imaging. Figure 31 shows the photograph of the TMA breadboard and TMA mounted on a test jig with a CMOS camera for imaging tests (Figure 32).

The results of the imaging tests are shown in Figs. 34-35 for on-axis and edge FOV respectively. Some vignetting observable in the on-axis image is due to the non-uniform illumination of the target and is not due to the instrument.

Images of the bar targets acquired with the micro-TMA breadboard are reported in Figure 33 (on-axis) and Figure 34 at the edge of the field of view.
LIMITATIONS AND USABILITY OF COMPACT HYPERSONTRALS

After the completion of the work we ask ourselves again the initial questions: is there any advantage in having a not so performing but small and cheap hyperspectral? Is there any application where a compact hyperspectral can deliver interesting measurements?

We verified, as we expected, that a Compact Hyperspectral delivers marginal performance to quantitatively measure chemical components of the observed scene, but we understood that in a number of applications the instrument could be used for early detection of anomalies, especially on areas offering a good radiance level, as for example crops. We also identified areas of optimization of the design, i.e. the LVF, and we believe that the overall performance could be improved by a better understanding of the instrument and of the retrieval algorithms. These improvements, even if marginal, will widen the operability of the instrument. So were the advantages of a compact hyperspectral and for which applications? We believe that a cheap, low power instrument used for early warning could enhance Earth Observation by targeting high resolution instruments on areas of specific interest.

THE ROADMAP: FROM CONCEPT TO LAUNCH

To develop a breadboard is only the first step to build flight hardware. The major hurdles to overcome are of both technical and programmatic nature: an engineering model is being planned to perform airborne measurements. This will give more insight on how to optimize the performance. It will be necessary to develop the electronics to drive the large area detector and the software to fine tune the retrieval algorithms.

The step to be taken after the engineering model has been tested is to prove that on-board real time processing can be handled. We firmly believe that the bandwidth necessary to transmit on ground all the data and the complexity of the ground segment will be show stoppers for a small and cheap instrument. Therefore we think that one the conditions to use the PhytoMapper on board a satellite is to deliver in almost real time the geo-referenced coordinated of the boundaries of the area of interest. It is in these two directions that we will be moving in the near future.

References