HYPXIM - AN INNOVATIVE SPECTROIMAGER FOR SCIENCE, SECURITY AND DEFENCE REQUIREMENTS

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Résumé

Cet article présente un aperçu des applications et des besoins de données hyperspectrales recueillis par un groupe ad-hoc d'une vingtaine de scientifiques français et d'utilisateurs Civil et de la Défense (i.a. dual). Ce groupe connu sous l'acronyme GHS (Groupe de Synthèse en Hyperspectral) a défini les exigences techniques pour une mission spatiale de haute résolution en hyperspectral répondant aux besoins des thèmes suivants: la végétation naturelle et agricole, les écosystèmes aquatiques côtiers et lacustres, les géosciences, l'environnement urbain, l'atmosphère, la sécurité et la défense.

La synthèse de ces exigences a permis de décrire les spécifications d'un satellite très innovant en terme de domaine spectral, de résolution spectrale, de rapport signal à bruit, de résolution spatiale, de fauchée et de répétitivité. HYPXIM est une mission hyperspectrale spatiale de nouvelle génération qui répond aux besoins d'une large communauté d'utilisateurs de données à haute résolution dans le monde.

Les principaux points ont été étudiés dans la phase 0 (pré-phase A) menée par le CNES avec ses partenaires industriels (EADS-Astrium et Thales Alenia Space). Deux concepts de satellites ont été étudiés et comparés. Le premier, appelé HYPXIM-C, vise à obtenir le niveau de résolution le plus élevé possible (15 m) réalisable en utilisant une plateforme de microsatellite. Les objectifs du deuxième, appelé HYPXIM-P, sont d'atteindre une résolution spatiale supérieure d'un facteur deux en hyperspectral (7-8m), un canal panchromatique (2m) et de fournir une capacité en infrarouge hyperspectral (100 m) sur un mini satellite.

La phase A HYPXIM a été récemment décidée. Elle démarre en 2012 en se concentrant sur le concept le plus performant. Le défi pour la mission HYPXIM qui a été sélectionnée est de concevoir un spectroimageur à haute résolution spatiale, sur un mini-satellite agile à moindre coût.

Ces études préliminaires ouvrent des perspectives pour un lancement possible en 2020/21 en fonction du développement des technologies critiques.

Mots clés : Satellite hyperspectral, Spectroscopie, Spécifications, Capteur optique.

Abstract

This paper provides an overview of hyperspectral applications and data requirements gathered by an ad-hoc group of French scientists and Defence users. This group known by the acronym GSH (Groupe de Synthèse sur l'Hyperspectral) has addressed clear and detailed technical requirements for a high spatial resolution hyperspectral mission on the following themes : study of vegetation, coastal and inland water ecosystems, geosciences, urban environment, atmospheric studies, security, and Defence.

The synthesis of these requirements substantially helped to set up consolidated space-based system requirements (i.e. mission requirements) in terms of spectral domain, spectral resolution, signal-to-noise ratio, spatial resolution, swath and revisiting period, which revealed the main key drivers for the design of a very innovative hyperspectral space instrument. HYPXIM is a new-generation hyperspectral concept which meets the needs of a wide community of users in the world.

During the phase 0, CNES with the support of industry (Astrium et Thales Alenia Space) has compared two different scenario. The first scenario, named HYPXIM-C, aims at finding out the highest possible resolution level (15 m) achievable using a microsatellite platform, whereas the goals of the second scenario, called HYPXIM-P, are to reach a higher spatial resolution (8 m), and to provide a TIR hyperspectral capability.

The HYPXIM phase A was recently decided and focused on the most performing concept, but without TIR capabilities. The challenges for the selected HYPXIM mission were to design an agil high resolution spectroimager on a mini-satellite.

Preliminary studies with industrial support show that this challenge can be taken to space around 2020/21 depending on the development of critical technologies (like specific detectors). Expected lifetime in orbit is 10 years, including end-of-life operations.

Keywords : *Hyperspectral satellite, Imaging spectroscopy, optical sensor specifications.*

1. Context

An ad hoc group of Science and Defense users was introduced at the instigation of the CNES Program Directorate Earth Observation team, with several objectives :

- Establish an up-to-date view of applications (science and Defence) and the characteristics (spectral, spatial and temporal sampling) of the data used to address these applications;
- Analyse future requirements of the user community, and identify current and future systems likely to address these requirements;
- Identify likely gaps in the provision of systems or support to the user community given the elements described above;
- Propose solutions to address the likely gaps identified.

The aforementioned group gave their recommendations which have led CNES to begin the study of the hyperspectral satellite at high spatial resolution: **HYPXIM**. This paper provides, in Section 2, a high level description of the analysis presented by the ad-hoc group GSH in each of six scientific themes where hyperspectral imagery is considered to bring significant advances. A brief overview is provided on Defence requirements. In addition, Section 3 presents the trade-offs made in the definition of missions for the phase 0 study. Section 4 proposes two mission concepts that satisfy the majority of the user requirements expressed by the GSH. Section 5 describes the final HYPXIM concept, and Section 6 provides conclusions.

2. Science and Defence Requirements

The following section describes the fundamental Science, Societal applications and Defence targets in six distinct themes selected for their current or potential involvement in exploiting hyperspectral data (Hyperspectral Synthesis Group Report, 2008). The six themes are: Vegetation, Inland and Coastal waters, Geoscience/Solid Earth science, Urban environment, Atmospheric sciences, and Defence requirements.

2.1. Vegetation

In the context of the ever growing influence of the ecological movement on our society, there is a strong societal demand for new scientific knowledge and expertise to help reorient current economic models toward sustainable development, protection of the natural environment, more environmentally friendly agricultural practices and monitoring of terrestrial ecosystems. Among the requirements described by the science community is the need to improve our ability to quantify, both on local and regional scales, plant health using indicators such as leaf water content, dry matter, and pigments. Leaf water content and dry matter content are two key parameters that provide the ability to map vegetation water content necessary for many environmental applications (forest fire hazards, climate change studies, desertification). In addition, information on the dry matter content enables the estimation of the ratio of carbon/nitrogen in a forest which provides the decomposition rate of the organic matter by micro-organisms in the soil. This in turn allows for an estimation of the release of CO_2 into the atmosphere, providing inputs to the study of the carbon cycle. The ability to distinguish between species based on variations in biochemical properties is derived from studies of ecosystems (see Figure 1) and their evolution under climate change and anthropogenic forcing.

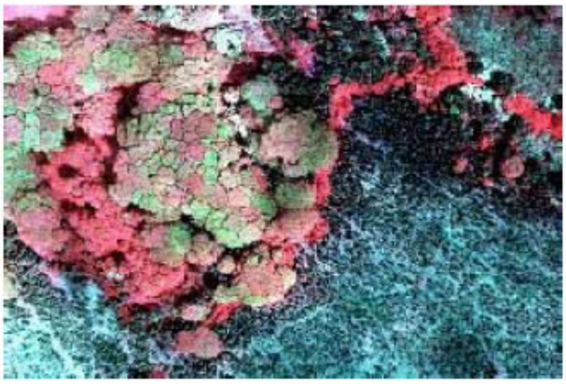


Figure 1 : Differentiation between plant species. This image, from the Carnegie Airborne Observatory, illustrates the ability to differentiate between different species based on spectral response. This enables quantitative studies on the impact of invasive specifies. In this image the silk tree and strawberry guava in a wetland in Hawaii, USA, are shown.

Spectral characteristics : 0.4-2.5 μm, resolution < 10 nm;

Geometric characteristics : Very high spatial resolution is useful for certain applications;

Temporal characteristics : Variable but can be critical during the growing season (10 days).

2.2. Costal and inland waters

One application which has significant potential in the near future, in line with legal requirements imposed at a European level, is that of water quality both of coastal and inland waters. While much progress has been made on the study of ocean colour using data from various sensors designed specifically for this purpose or ad-hoc, coastal and inland waters present additional challenges including more complex mixtures of organic and inorganic material, particles and dissolved material. In addition, the study of coastal waters is further complicated by its high spatio-temporal variations. Main water quality parameters that can be derived from hyperspectral imagery include : type and size of suspended particles, toxic algal blooms, cyanobacteria, eutrophication by green algal blooms. Hyperspectral imagery is used to complete large scale mapping of macro or microscopic benthic communities particularly in monitoring eutrophisation by green algae or the state of coral reefs. Hyperspectral imagery has also been effective, particularly in less turbid waters, in improving estimations of the bathymetry through better characterisation of the sea bottom.

In addition to the research activities of the scientific community in this domain, in recent years, and due mainly to legal constraints, a significant market has grown in providing hyperspectral surveys and analysis of the images acquired to address diverse questions associated with the management of these particularly fragile ecosystems.

Spectral characteristics : 0.3-1 μm for the majority of applications. Extended to 2.5 μm for characterisation of sediments, resolution < 10 μnm. Signal-to-Noise Ratio (SNR) >400.

Geometric characteristics : Very high spatial resolution (<10 m).

Temporal characteristics : Variable, strong constraints for certain applications (1 day).

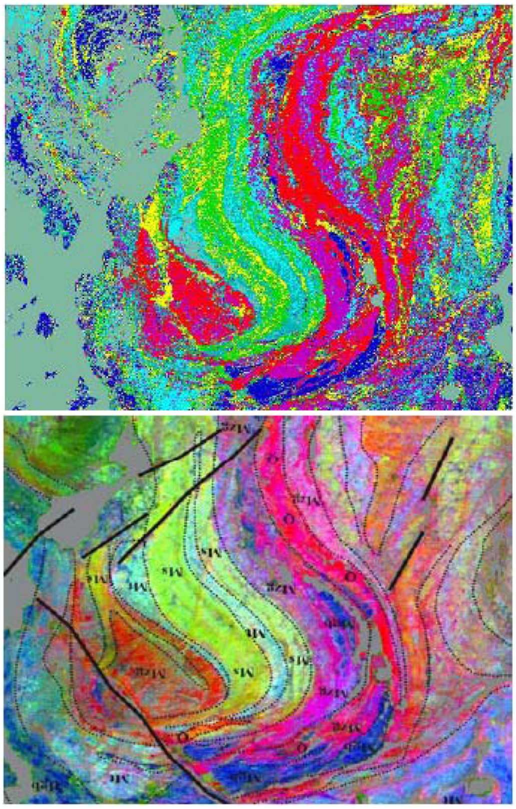


Figure 2 : Comparison between a classifications of (a) a Proba-1 hyperspectral image, and (b) a ground truth geological mapping. Baffin Island, Canada. 🟦 Veg/metagabbro – ■ Metatonalites – ■ Metatonalites – 🟥 Quarzites – 🟩 Psammites – 🟪 Monzo + granites – 🟨 Psammites.

2.3. Geoscience/Solid Earth science

A domain which has been a constant user of hyperspectral imagery in the last thirty years and, as such, has been the driver behind the development of this technology is geology. Hyperspectral sensors have, from the 80's, opened a new era in geological mapping allowing, in addition to the structural/tectonic information, direct access to the mineralogical composition of exposed rocks. This unique capacity means that hyperspectral imagery is used as a unique source of information for all mining and oil companies for prospecting, but also in rehabilitation of abandoned mines. Here, three main themes were described by the GSH: (1) prospecting for minerals and oil; (2) environmental geology; (3) soil degradation/quality. Information on mineralogical content providing specific markers for certain minerals (as shown in Figure 2) or oil has been the primary commercial use of hyperspectral imagery over the past two decades.

New markers are being used for a wider range of minerals as the experience of the exploration industry increases. The potential use of hyperspectral imagery in the remediation of abandoned mines has been demonstrated in several past projects, these have recently been extended to include industrial sites in general. The monitoring of soil quality using indicators such as surface crusts, erosion processes, salinization has been demonstrated in research projects. Mapping of swelling clay hazard has also been demonstrated using hyperspectral imagery.

Spectral characteristics : 0.4-2.5 μm, thermal IR 8-12 μm, resolution < 10 nm in VNIR/SWIR.

Geometric characteristics : Mid to High spatial resolution (<20 m).

Temporal characteristics : Less than monthly for certain environmental monitoring applications (10 days).

2.4. Urban environment

On this up-coming theme, three broad topics were identified as potentially benefiting from high spectral resolution imagery:

- **Characterisation and mapping of urban materials**. Hyperspectral imagery has shown some promise in recent studies in providing discrimination between different man-made materials due to differences in spectral signature. However, the urban environment is characterised by high spatial variability. This thus requires very high resolution images.

- **Air quality**. Some recent studies have shown the feasibility of obtaining useful information on aerosols and human emissions over urban environments. While the spectral resolution of hyperspectral imagery is less than that of profilers such as IASI, the spatial sampling is more appropriate for urban environments and complements ground based measurements.

- **Characterisation of urban vegetation and biodiversity**. The potential of hyperspectral imagery in discriminating plant species, as described in the paragraph on "vegetation", is of particular interest in the urban environment. Here, as the thermal and pollution-reducing effect of vegetation varies according to the species, the spatial distribution of species is of great interest in modelling a specific urban area.

Spectral characteristics : 0.4-2.5 μm, thermal IR 8-12 μm, resolution < 10 nm in VNIR/SWIR.

Geometric characteristics : Very high spatial resolution (5 m).

Temporal characteristics : No strong recommendation in general. Can be critical during a crisis (3-5days).

2.5. Atmospheric sciences

The GSH identified in this domain several innovative research themes which take their origin in the atmospheric corrections necessary for a correct use of hyperspectral imagery. It should be noted that this domain is richly endowed with specific satellite missions each targeting one or several parameters of themes of interest for atmospheric scientists. The objective of studying the possibilities offered in this domain was to attempt to identify potential "spin-off" applications that may emerge. Several topics were identified, and would benefit from further study:

- **Detection of surface phenomena**. Imagery can provide useful advantages over profilers in detecting horizontal variations in the atmosphere which are produced when a surface process producing the atmospheric effect. Phenomena such as volcanic eruptions, fires or sources of methane could be detected using hyperspectral imagery.

- **Characterisation of aerosols and clouds**. While significant information on these phenomena can be derived from multispectral imagery with a much lower spatial resolution than the hyperspectral systems proposed here, some original applications could be attempted: measure of aerosol altitude through combining the mesure of gas absorption and its diffusion properties; aerosol/cloud interactions requiring a high spatial resolution.

- **Pollution/Air quality**. Monitoring of low level atmospheric pollution (specifically NO_2 and NO) could potentially be of interest provided the spectral resolution was high enough. The required spatial resolution is around 1 km.

2.6. Defence requirements

The Defence requirements described by the GSH are principally derived from work undertaken across various structures in the French Defence sector. Much work has been done in the past ten years studying the potential use of hyperspectral imagery for Defence applications. A number of key applications have been identified and the optimal hyperspectral characteristics provided. Among these, three should be noted in particular : characterisation of coastal areas (bathymetry); trafficability; detection/characterisation of objects/anomalies. Requirements have been provided in previous sections for the two former points cited above. The third point can be decomposed into anomaly detection and object characterisation. Anomaly detection using simple processing strategies has been demonstrated. It has also been possible to demonstrate that with suitably selected spectral bands buildings and roads can be characterised using high resolution imagery.

Spectral characteristics : 0.4-2.5 μm, thermal IR 8-12 μm, resolution < 10 nm in VNIR/SWIR.

Geometric characteristics : Very High spatial resolution (5 m).

Temporal characteristics : Short revisit period required (24-60 hours).

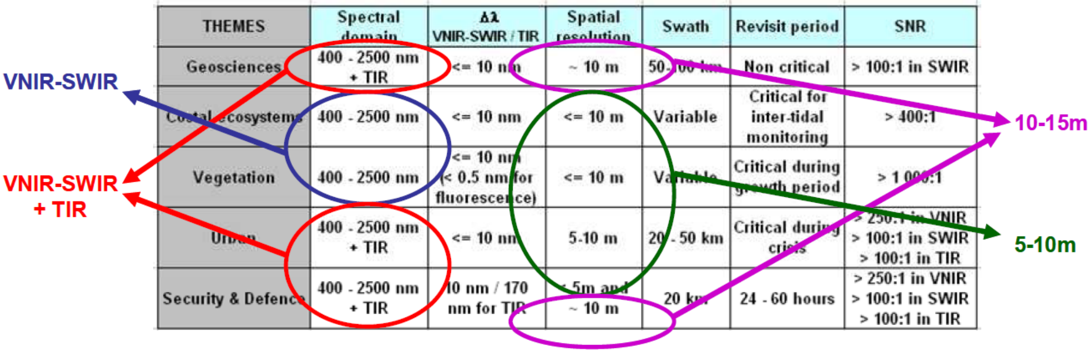
3. Overall Mission Requirements

Following the publication of the GSH report at the end of 2008, CNES program directorate decided to proceed with a phase 0 study of a hyperspectral system, HYPXIM, targeting the user requirements provided by the GSH.

The synthesis of all these needs (Figure 3) has been described in the HYPXIM Mission Requirements Document (MRD), which helped to set up a panel of consolidated specifications in terms of spectral domain, spectral resolution, signal-to-noise ratio, spatial resolution, swath and revisit period (Carrère, 2012). This led to the main drivers presented below for the definition of an innovative hyperspectral instrument from space (HYPEX, 2010; Hosford et al., 2010).

3.1. Spectral domain : VNIR, SWIR and TIR

The spectral domain of interest extend homogeneously from 400 nm to 2500 nm, covering both Visible and Near-Infra Red (VNIR) as well as SWIR (Short Wave Infra-Red) wavelengths. Also, another application community expressed the needs of new hyperspectral data in the Thermal Infra-Red domain (TIR) .



THEMES	Spectral domain	Δλ VNIR-SWIR / TIR	Spatial resolution	Swath	Revisit period	SNR
Geosciences	400 - 2500 nm + TIR	<= 10 nm	~ 10 m	50-100 km	Non critical	> 100:1 in SWIR
Coastal ecosystems	400 - 2500 nm	<= 10 nm	<= 10 m	Variable	Critical for inter-tidal monitoring	> 400:1
Vegetation	400 - 2500 nm	<= 10 nm (< 0.5 nm for fluorescence)	<= 10 m	Variable	Critical during growth period	> 1 000:1
Urban	400 - 2500 nm + TIR	<= 10 nm	5-10 m	20 - 50 km	Critical during crisis	> 250:1 in VNIR > 100:1 in SWIR > 100:1 in TIR
Security & Defence	400 - 2500 nm + TIR	10 nm / 170 nm for TIR	< 5m and ~ 10 m	20 km	24 - 60 hours	> 250:1 in VNIR > 100:1 in SWIR > 100:1 in TIR

Figure 3 : Summary table of mission requirements expressed by the four main science user groups and Defence users.

3.2. Spectral resolution and Signal-to-Noise Ratio

In VNIR and SWIR most of the needs impose on us narrow contiguous bands less than 10nm, throughout the whole spectrum ; in TIR, the spectral resolution varies from 100 nm to 200 nm according to applications. The targeted Signal-to-Noise Ratio (SNR), defined in relation with a reference luminance, mainly depends on the spectral domain. These mission requirements are gathered in Table 1.

Domain	**Spectrum** (nm)	**Bandwidth** $\delta\lambda$ (nm)	**SNR**
VIS	400-700	10	$\geq$250:1
NIR	700-1,100	10	$\geq$200:1
SWIR	1,100-2,500	10	$\geq$100:1
PAN	400-800	400	$\geq$90:1
TIR	8,000-12,000	100/200	NEdT<0,5 K

Table 1 : Spectral requirements for HYPXIM mission.

3.3. Spatial resolution : two levels are chosen

Depending of the applications, the needs for Ground Spatial Resolution (GSR) are categorized into three different levels : 20 meters and larger (atmosphere), from 10 to 15meters (geosciences, agriculture), 10meters and smaller (Coastal and land ecosystems, biodiversity, Urban applications, Security and Defence).

Considering the performances of the first generation of planned European hyperspectral missions, CNES has excluded the class between 20 and 30 meters which is already targeted by EnMAP and PRISMA. So, the spatial resolution for HYPXIM studies was set between 5 and 15 meters maximum, which is both a technically complex and innovative approach. For TIR hyperspectral data, the spatial resolution required for this preliminary study is roughly 100 meters.

3.4. Swath no less than 15 km

A minimum swath of 15 km is requested by the main applications.

3.5. Revisit frequency is mostly critical

A daily observation is ideally required for security or Defence, but a revisit of 3-day seems acceptable for many products related to this theme. For other applications such as urban or geosciences, refreshing data is less critical.

3.6. From ground reflectance to at-sensor radiances

For each spectral band, the at-sensor radiance specifications has been defined for the different themes (Briottet et al., 2011). The observable domain (L2), depends mainly on the object reflectance, the geographical position, the Sun illumination level, and the atmospheric conditions (Figure 4).

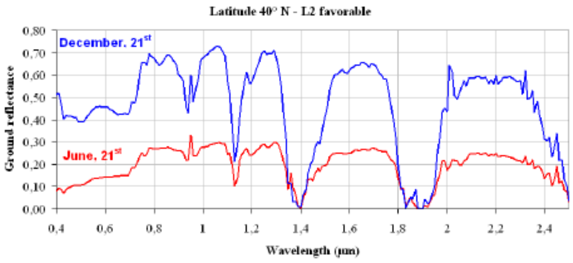


Figure 4 : Ground reflectance providing an at-sensor radiance of L2 favorable, for a site located at 40^{o}N latitude, at two dates on June, 21st and December, 21st.

Two main system specifications have been established as baselines for the phase 0 study (EADS-ASTRIUM, 2011; Thales Alenia Space, 2011).

- HYPXIM-C (Challenging):
  - Spatial resolution: 15 m;
  - Spectral coverage and resolution: 0.4-2.5 μm;
  - Spectra resolution: 10 nm;
  - Image size and acquisition capacity: 30 km × 30 km (*option A*) or 15 km × 15 km (*option B* with an additional panchromatic channel).

- HYPXIM-P (Performance):
    - Spatial resolution: hyperspectral - 8 m, PAN: 2 m, TIR: 100 m;
    - Spectral coverage and resolution: 0.4 - 2.5 μm (10 nm); 8-12 (40 bands from 90 to 150 nm);
    - Image size and acquisition capacity: 16 km × 16 km.

3.7. Option "C" concept

HYPXIM-C spatial segment is composed of two identical satellites orbiting on a sun-synchronous orbit at 650 km. Both accommodate the same hyperspectral payload. The instrument diameter being limited due to the small size of the platform, the satellite has to slow down when taking hyperspectral images so as to enhance the number of collected photons in all illuminated spectral bands. Each satellite weighs less than 200 kg at launch and fits into a sizing envelope of 600 x 600 x 1 350 mm, to be compatible with a launch on either Soyuz, Vega, Ariane 5 or Falcon 1E. A solar array provides around 200 W at the beginning of the mission; being able to rotate in order to maximise incoming solar energy flux. Expected lifetime in orbit is five years, including end-of-life operations.

3.8. Option "P" concept

HYPXIM-P spatial segment is composed of one satellite orbiting on a sun synchronous orbit at 660 km.

The payload is made up with three instruments :

- An hyperspectral instrument (referred to as HX-VNIR-to-SWIR) covering the 0.4 to 2.5 μm domain composed of a telescope and of a spectrometer;
- A panchromatic channel (PAN), using the same telescope with spatial or radiometric separation;
- A thermal infra-red hyperspectral instrument (referred to as HX-TIR) with its own telescope and spectrometer.

The mini-satellite weighs around 605kg at launch and fits into an envelope of 1,400 x 1,200 x 2,600 mm, so as to be compatible with a launch on Soyuz, Vega, Ariane 5 or Falcon 1E.

4. HYPXIM a new generation system with hyper performances

During the period 2011-2012 different activities have been conduced by the CNES in collaboration with its scientific, Defence and industrial partners in order to evaluate these different concepts in an experimental approach:

- Validation of instruments performance and concepts via qualified and developed breadboard (full-scale test bench);
- Parametric simulation of HYPXIM data (using airborne campaigns) for the consolidation of specifications related to the spatial resolution and the signal quality (SNR and luminance level specifications), calibration/validation process definition, etc.;
- Technology readiness level (TRL) and economic comparison.

The HYPXIM phase A was recently decided, with the selection of the most performant concept, but without the TIR Hyperspectral payload considered less mature and more risky than the others instruments.

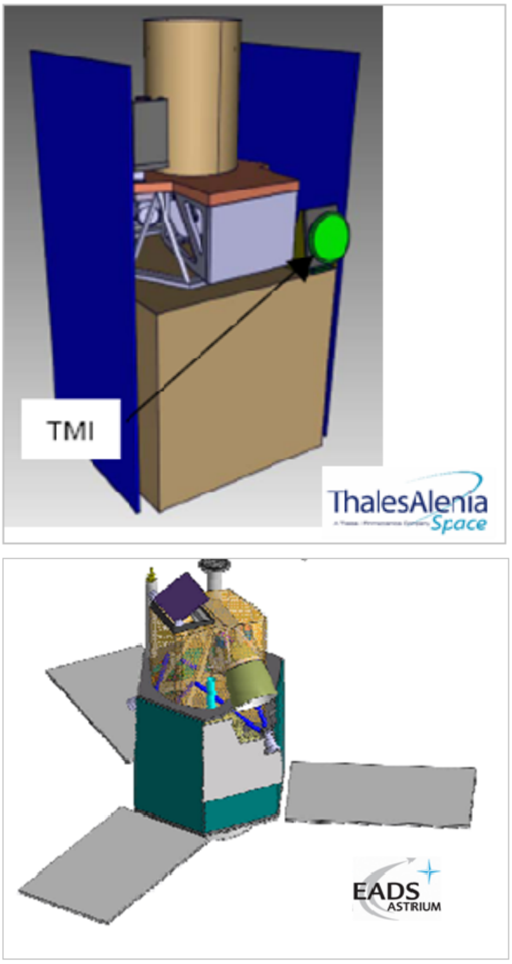


Figure 5 : HYPXIM satellite overview by Thalès Alenia Space (above) and EADS-ASTRIUM (left) [CNES and industrial property - all rights reserved].

The entire payload weighs about 115 kg, and the maximum requested power during imaging phases is about 150 W. The HYPXIM "HX" instrument (VNIR-to-SWIR) is composed by a Korsch or a TMA telescope with a pupil diameter of around 450 mm opened at F/4 or F/2.5 and coupled with a compact and innovative spectrometer.

The design of HX instrument is very compact and is inherited from a new concept that will not be detailed here (Hebert et al., 2012). It is composed of two prisms and of new generation detector 2,000 x 360 pixels (to be developed by European companies). The focal plane is 30-mm large. The hyperspectral detectors HgCdTe are maintained at 150 K thanks to a small redounded cryogenic device. FTM is better than 0.22, and instrument SNR meets the requirements recalled in Table 1 with margins except in the 400-450 nm zone and, obviously, in the spectral windows corresponding to atmospheric absorptions.

The spatial resolution of the hyperspectral image is as small as 8 meters, which represents a breakthrough in civilian hyperspectral systems. What is more, the fusion of panchromatic (1.85 m spatial resolution) and hyperspectral images on-board should allow to obtain Hyperspectral fused products at a resolution better than 2 meters.

For the hyperspectral instrument, the spectral resolution is 10 nm through the whole spectrum from 0.4 to 2.5 μm. Therefore the hyperspectral image is composed of 210 different spectral bands which are all downloaded after on-board adaptive compression. At VNIR-to-SWIR and PAN output, a square image of 16 x 16 km weighs around 7 Gigabytes. All bands are downloaded after on-board compression.

The mini-satellite weighs around 850 kg at launch (Figure 5) is compatible with Soyuz or Vega. Expected lifetime in orbit is 10 years, including end-of-life operations constraints.

5. Conclusion and perspectives

HYPXIM is a new-generation hyperspectral concept (Figure 6) which meets the needs of a new wide community currently using in situ and high-resolution hyperspectral images (e.g., on airborne, or UAV).

This innovative satellite allows:

- Enhanced spatial resolution up to 8 m with a swath of 16 km compatible to Pleiades;
- Thanks to their agil platform, higher revisit frequency in "on-event mode" (up to three days) for Security and Defence actors;
- Technological miniaturization which allows an innovative mini-satellite less than 1 ton;
- Multi-sensors fusion products using on board PAN and Hyperspectral data.

The next steps for HYPXIM are first to keep on the Research & Development plan prepared for the HYPXIM missions in the following axis :

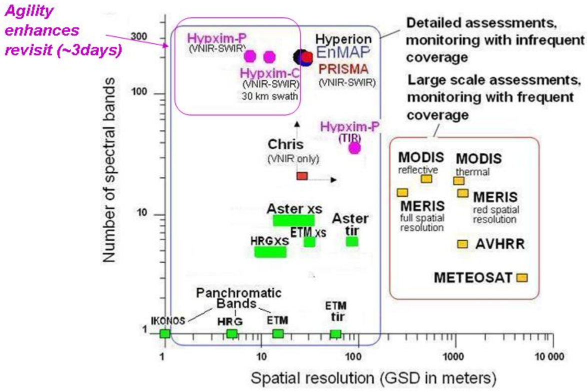


Figure 6 : Position of HYPXIM missions w.r.t. other hyperspectral satellite systems.

- Technical activities : development of a new detector;
- Product activities: multi-sensor fusion (hyperspectral + panchromatic), new thematic algorithms, etc.

Secondly, the HYPXIM phase A is taking place in CNES from mid-2012 to 2015. After this period, phases B/C/D/E1 should be decided for a launch in 2020/2021 depending on the development of critical technologies (like specific detectors) and international cooperation interest.

Acknowledgments to Hyperspectral Mission Group

President: Rémi MICHEL (CEA), Secretary: Rodolphe MARION (CEA). Science coordinator: Véronique CARRERE (Université de Nantes).
Members: Xavier BRIOTTET (ONERA), Sabine CHABRILLAT (GFZ), Stéphane CHEVREL (BRGM), Jean-Marie FROIDEFOND (Université de Bordeaux 1), Steven HOSFORD (CNES), Stéphane JACQUEMOUD (IPGP), David LAUBIER (CNES), Marie-José LEFEVRE-FONOLLOSA (CNES), Camille LELONG (CIRAD), Marc LENNON (Actimar), Commandant Frédéric LIEGE, (Etat-major des Armées), Eric MALIET (EADS-Astrium), Grégoire MERCIER (ENSTB), Philippe PRASTAULT (DGA), Pascal PRUNET (Noveltis), Serge TARIDE (Thales Alenia Space), Christiane WEBER (Université de Strasbourg).

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