HYPXIM – A HYPERSPECTRAL SATELLITE DEFINED FOR SCIENCE, SECURITY AND DEFENCE USERS

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ABSTRACT

Based on sound mission technical requirements provided by a group of national experts in hyperspectral imagery [1], CNES has been conducting pre-phase A study with the support of Astrium and Thales Alenia Space, in non-concurrent engineering. The first promising results helped to propose HYPEX to ESA Earth Explorer 8 call for missions [4]. This paper summarizes the results up to now. Two mission scenarios were defined : the first scenario, named HYPXIM-Challenging**,** aims at finding out the highest possible performance level achievable using a microsatellite platform, whereas the goals of the second scenario, called HYPXIM-Performance, are to reach a higher spatial resolution and to provide a TIR hyperspectral capability.

Index Terms— Hyperspectral satellite, Imaging spectroscopy, Optical sensor specifications

1. HYPXIM MISSION OBJECTIVES

Thanks to the broad federation of hyperspectral users in France, a national group of scientists could collegially address clear and very detailed science technical requirements for a high resolution hyperspectral mission in the themes : study of vegetation, coastal and inland water ecosystems, geosciences, urban environment, atmospheric studies, security and defence [1].
The synthesis of these requirements helped a lot 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 revisit period, which revealed the main key drivers for the design of a hyperspectral space instrument.

1.1. HYPXIM : a key to new applications

The major technical requirements accessible by high-resolution hyperspectral data are synthesized in [6]. These technical requirements are given below.

1.2. Spectral domain : VNIR, SWIR and TIR

The wavelengths of greatest interest spread quite homogeneously from 400 nm to 2500 nm, covering both Visible and Near-InfraRed (VNIR) as well as SWIR (Short Wave InfraRed) domains. Besides that, some applications also need to collect multispectral or hyperspectral (HX) data in Thermal InfraRed (TIR) wavelengths.

1.3. Spectral resolution and Signal-to-Noise Ratio

In VNIR and SWIR, spectral resolution shall be less than 10 nm throughout the entire continuum spectrum to cover most of the needs ; in TIR, the needs vary 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. 100:1 is sufficient for SWIR and TIR, whereas higher values are requested for NIR (200:1) and VIS (250:1).
These mission technical requirements are gathered (Tab. 1).

Domain	Spectrum (nm)	Bandwidth $\delta\lambda$ (nm)	SNR
VIS	400-700	10	≥ 250:1
NIR	700-1100	10	≥ 200:1
SWIR	1100-2500	10	≥ 100:1
PAN	400-800	400	≥ 90:1
TIR	8000-12000	100/200	> 100:1

Table 1. Spectral requirements for HYPXIM mission

1.4. Spatial resolution : 3 levels

The needs for Ground Spatial Resolution (GSR) are categorized into 3 different levels : 20 meters and larger, from 10 to 15 meters, 10 meters and smaller.
As the GSR class between 20 and 30 meters is already targeted by the first generation of European hyperspectral missions (EnMAP and PRISMA), the spatial resolution for HYPXIM studies was set to 15 meters maximum, which is both a technically complex and innovative approach.
For new applications TIR hyperspectral data, the required spatial resolution is roughly 100 meters.

1.5. Swath

As requested by a few applications, a minimum swath of 15 km is specified for HYPXIM missions.

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1.6. Revisit frequency

For some applications related to security or defence, a daily revisit is required but a 3-day revisit seems acceptable. For other applications such as urban or geosciences, revisit time is less critical.

1.7. From radiance to ground reflectance maps

For a better understanding, the at-sensor radiances specifications [6] are converted into observable ground reflectances, according to the observation latitude and the sun-zenithal angle. For instance, at 400 nm, a pre-defined at-sensor radiance (called L2 favorable) [6] is reached on June, 21 for a ground reflectance of 0.1 at 40°N latitude (fig. 1).

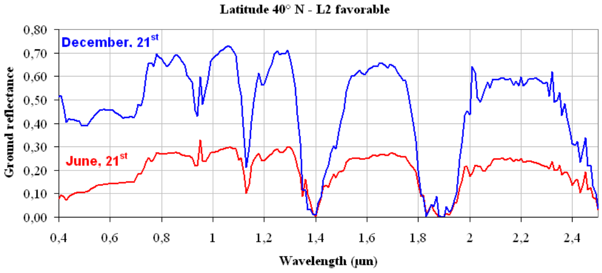

Figure 1 : Ground reflectance providing an at-sensor radiance of L2 favorable, for a site located at 40°N latitude, at 2 dates on June, 21st and December, 21st

2. HYPXIM-C : NOT A MICRO-CHALLENGE

The main challenge for HYPXIM-C mission design is to merge two almost antinomic constraints : a small platform and a high-resolution hyperspectral instrument. Studies lead by CNES with industrial support [2] [3] show that this challenge can be taken to space before 2020 in the frame of a mission HYPXIM-C "Advanced" (HYPXIM-CA), or even sooner in the frame of a mission HYPXIM-C "Basic" (HYPXIM-CB).

2.1. HYPXIM-C mission concept

HYPXIM-C spatial segment is composed of 2 identical satellites on a sun-synchronous orbit at an altitude of 650 km. Both satellites accommodate the same hyperspectral payload (described hereafter) with a 15-km (for HYPXIM-CB) or 30-km (for HYPXIM-CA) swath.
Two separate revisiting modes are defined : a "routine mode" to cover the maximum of surfaces and an "on-event mode" dedicated to collect data on specific zones as quickly as possible. Due to the relatively small swath, the revisit period at nadir for the 2-satellite system is about 30 days. Thanks to convenient actuators, revisit period is as small as 3 days for sites spread between 60° South and 60° North latitudes, using the platform's agility to get off-track images.

Due to the small size of the platform, the instrument's diameter is limited. Therefore, the satellite has to slow down when taking hyperspectral images in order to accumulate as many photons as possible in illuminated spectral bands.
System imaging capacity for both satellites is more than 150 square images per day, downloaded through X-band at 160 Mbps either to ground or to mobile stations. The ground track between 2 consecutive square images is about 800 km, but one image can be as long as 500 km if requested.
The spatial resolution of both satellites is 15 meters at nadir, which represents a breakthrough compared to Hyperion and EnMAP for example. An additional panchromatic channel at a resolution of about 3.5 meters allows to combine panchromatic and hyperspectral images to get HX-PAN melted products.
The spectral resolution is 10 nm all through the 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 compression.
A solar array provides around 200 W at the beginning of the mission; and has the capability to rotate to maximise incoming solar energy flux from the Sun.
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 Soyuz, Vega, Ariane 5 or Falcon 1E.
Expected lifetime in orbit is 5 years, including end-of-life operations (deorbitation boost included in the fuel assessment).

2.2. HYPXIM-CA payload and instrument overview

The payload is composed of a TMA (Three-Mirror Astigmatic) telescope coupled with a compact prism-based spectrometer.
FTM is better than 0.15 and instrument SNR meets the requirements recalled in Tab. 1 with margins excepted in the 400-450 nm zone and, obviously, in the spectral windows corresponding to atmospheric absorptions.
Calibration is performed either through a mechanism located at telescope entry (Sentinel 2 concept) or through the use of a wheel mechanism between the telescope and the spectrometer (MERIS concept).

At instrument output, a square image of 30 x 30 km weighs around 6 Gbytes.
The payload weighs about 60 kg and fits into a box of 600 x 600 x 750 mm. The requested power during imaging phases is about 50 W.

The pupil diameter is roughly 170 mm opened at F/5. The hyperspectral instrument is very compact and its design is derived from a new concept than will not be detailed here (proprietary concept). It is composed of prisms and of new generation detector 2000 x 360 pixels (to be developed in European industry). The focal plane is 30-mm large.

The hyperspectral detectors are maintained at 175 K thanks to a small non-redounded cryogenic device.

2.3. HYPXIM-CB : to a new instrumentation design

HYPXIM-CA payload is very promising, but needs the development of a new generation detector. Therefore CNES decided to conduct the design of a HYPXIM-CB payload inherited from HYPXIM-CA but with an "off-the-shelf" policy regarding its components.
The very first results show that the instrument is even more compact.

3. HYPXIM-P : HYPER-PERFORMANCE

The main challenge for HYPXIM-P mission is to design a very high-resolution instrument on a mini-satellite.
Studies lead by CNES with industrial support [2] [3] show that this challenge can be taken to space before 2020.

3.1. HYPXIM-P mission concept

HYPXIM-P spatial segment is composed of one satellite on a sun-synchronous orbit at an altitude of 660 km. It accommodates a hyperspectral instrument, a panchromatic channel and a TIR instrument (described hereafter). Thanks to a 16-km swath and powerful on-board actuators, revisit period is as small as 3 days for 50 different sites spread between 60° South and 60° North latitudes, and revisit period near nadir (i.e. at nadir +/- 6°) is 19 days.

System imaging capacity is more than 120 square images per day, representing roughly 30 000 km² / day to be downloaded through X-band at 270 Mbps either to ground or to mobile stations. Thanks to a great on-board agility, the ground track between 2 consecutive square images is less than 230 km. HX imaging capacity is mainly limited by the need for high spatial resolution which forces the satellite to slow down when taking hyperspectral images.

The spatial resolution of the panchromatic image is less than 2 meters.
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 and hyperspectral images on-board should allow to obtain Hyperspectral PAN-sharpened products at a resolution of 2 meters.
For TIR, the spatial resolution is 100 meters.

The spectral resolution is as low as 10 nm throughout the entire 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.
For the hyperspectral TIR instrument, the spectral resolution is between 90 and 150 nm with 40 bands in the 8-12 µm domain.
All bands are downloaded after on-board compression.

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

Two fixed solar arrays provide around 1200 W at the beginning of the mission.

Expected lifetime in orbit is 10 years, including end-of-life operations (deorbitation boost included in the fuel assessment).

3.2. HYPXIM-P payload description

The payload is made up with 3 instruments :

- a 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,
- an thermal infrared hyperspectral instrument (referred to as HX-TIR) with its own telescope and spectrometer.

At HX-VNIR-to-SWIR output, a square image of 16 x 16 km is around 7 GB big, while HX-TIR image size is around 800 times smaller.

The entire payload weighs about 105 kg. The maximum requested power during imaging phases is about 300 W.

3.3. HYPXIM-P instrument overview

The VNIR-SWIR hyperspectral instrument (HX-VNIR-to-SWIR) is composed by a Korsch telescope with a pupil diameter of around 430 mm opened at F/4 and coupled with a compact spectrometer.

The design of HX-VNIR-to-SWIR is very compact (less than 88 kg) and is inherited from a new concept than will not be detailed here (proprietary concept). It is composed of 2 prisms and of new generation detector 2000 x 360 pixels (to be developed in European industry). The focal plane is 30-mm large.
The hyperspectral detectors are maintained at 175 K thanks to a small redounded cryogenic device.

MTF (Modulation Transfer function) is better than 0.18, and instrument SNR meets the requirements recalled in Tab. 1 with margins except in the 400-450 nm zone and, obviously, in the spectral windows corresponding to atmospheric absorptions. Calibration means possibilities are the same as for HYPXIM-C satellite.

Concerning the panchromatic instrument, FTM is better than 0.11 and SNR is above 250:1.

The thermal infrared hyperspectral instrument (HX-TIR) instrument is composed by a dedicated telescope coupled with a specific spectrometer on which the flux is dispersed by a prism. For HX-TIR, the pupil diameter is roughly 60 mm at F/3.5. The TIR focal plane is less than 10-mm large and the detectors are maintained at around 55 K thanks to a redounded cryogenic device. The Signal-to-Noise is better than 0.3 K. Calibration can be based on black bodies implemented on-board. HX-TIR weighs around 14 kg.

4. AN INTERNATIONAL CHALLENGE

Large scale imagers like Severi (Meteosat) or MERIS (Envisat) give a high frequent global monitoring using multispectral and non-contiguous hyperspectral low resolution data.
On the other side, detailed assessments are delivered by high resolution multispectral or hyperspectral systems like Thematic Mapper, ASTER, CHRIS or Hyperion but with small and or infrequent coverage. In this category PRISMA and ENMAP will give, from 2014 onwards, a capacity to monitor the full VNIR-SWIR domain with contiguous narrow bands.

HYPXIM is a new-generation hyperspectral concept which meets the needs of a wide community of users in the world, allowing (Fig.2) :

- enhanced spatial resolution from 15 m without swath reduction (30 km) up to 8 m ;
- higher revisit frequency in "on-event mode" (up to 3 days) for Security and Defence actors ;
- technological miniaturization which allows microsatellites to achieve high-resolution hyperspectral low-cost demonstration mission by 2018 ;
- an innovative TIR Hyperspectral capability ;
- multi-sensors fusion products using on board PAN and hyperspectral data.

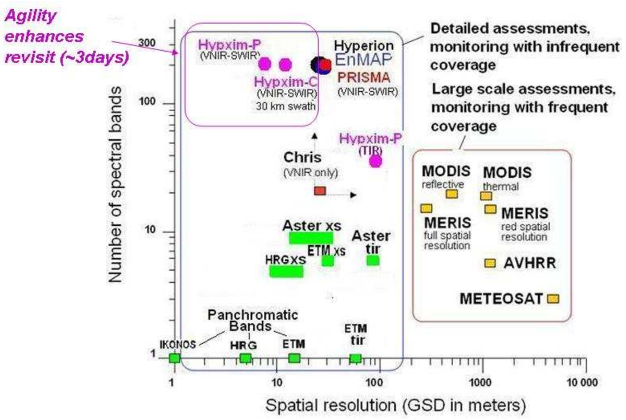

Figure 2 : Position of HYPXIM missions w.r.t. other hyperspectral satellite systems

5. CONCLUSION

Fostered by HYPXIM, other activities are on-going at CNES :

- system activities : consolidation of specifications related to input signal (SNR and luminance specifications, calibration/validation process definition, etc.), validation of instruments performances and concepts via ground test bench, simulation of HYPXIM data (using airborne campaigns)
- « technical » activities : development of the enhanced microsatellite platform Myriade New Generation, new adaptive compression algorithms.

Next steps for HYPXIM are first to keep on the Research & Development plan preparatory for both HYPXIM missions in the following axis:

- « technical » activities : development of 2 000 pixels VNIR-SWIR detector (for HYPXIM-CA),
- « product » activities : multi-sensor fusion (hyperspectral + panchromatic), new thematic algorithms, etc.

In the short term a phase A will take place in CNES in late 2011 based on technical requirements coming from the pre-phase A analysis by the Hyperspectral Mission Group.

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