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PHySIS

Sparse Signal Processing Technologies for HyperSpectral Imaging Systems

INSTRUMENT: Bottom-up space technologies at low TRL
OBJECTIVE: COMPET-06-2014

D2.2 Scenario descriptions and system requirements

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1. Introduction

1.1. Scope

In this deliverable (D2.2, WP2), we review the scenario descriptions, along with the associated requirements and system architectures to be addressed in the framework of PHySIS. More specifically, exact descriptions of the implementation requirements are given for the building components constituting the on-board and ground-based[1] units of our integrated hyperspectral imaging (HSI) platform. For the former, on-board unit, we primarily focus on the following tasks: i) hyperspectral (HYP) data acquisition; ii) HYP data compression; iii) on-board storage; iv) HYP data transmission. On the other hand, for the later, ground-based unit, we provide the algorithmic and implementation requirements for maximizing i) the restoration and ii) understanding performance of the acquired HYP data. Doing so, we guarantee maximum performance and transparency for both the individual components and the integrated end-to-end system.

1.2. Purpose

In deliverable D2.1 of WP2 we provided an overview of the state-of-the-art HSI systems in various distinct application areas, such as in space missions, medical diagnosis, food quality assessment, art and history masterpieces preservation, and criminology, just to name a few.

This deliverable, D2.2, analyses the specific scenario descriptions and system requirements, which will comprise the driver towards developing an integrated HSI platform within the PHySIS project. In particular, D2.2 aims at precisely defining and analysing the following aspects for spaceborne and terrestrial scenarios separately, which will be further used as benchmarks for setting the minimal targeted requirements of the PHySIS HSI platform:

[1] The term *ground-based unit* will be used to denote the central data processing unit for both spaceborne and terrestrial applications.

- ✓ **On-board processing unit:** Describe the operational specifications and requirements for hyperspectral data acquisition, data compression, on-board storage, and data transmission to a central processing unit.

- ✓ **Ground-based processing unit:** Describe the algorithmic specifications and performance requirements for achieving maximum enhancement (restoration) and understanding of the acquired hyperspectral information.

This document contributes to the detailed description of the scenario descriptions and the associated system requirements, which will guide the algorithmic and architectural developments in the subsequent WPs. It is emphasized again that the specific scenario description details and system requirements will be updated accordingly during the project's evolution, based on the results to be achieved within each of the specific activities of the other technical WPs, so as to attain maximal performance gains.

1.3. Applicable documents

[AD 01] PHySIS_Proposal-SEP-210155336

1.4. Reference documents

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[RD 02] ECSS-E-ST-40-06C, ECSS Space Engineering – Software – (issued on 6 March 2009)

[RD 03] CCSDS 311.0-M-1, Reference Architecture For Space Data Systems, September 2008

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[RD 05] Image Data Compression, Issue 2, (Green Book) CCSDS 120.1-G-2, Washington, D.C.:CCSDS, February 2015

[RD 06] CCSDS File Delivery Protocol (CFDP) – Recommendation for Space Data System Standards, Issue 4, (Blue Book) CCSDS 727.0-B-4, Washington, D.C.: CCSDS, January 2007

[RD 07] AOS Space Data Link Protocol – Recommendation for Space Data System Standards, Issue 2, (Blue Book) CCSDS 732.0-B-2, Washington, D.C.: CCSDS, July 2006

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[RD 23] V. Ashok, D. Reddy, and R. Raskar. "Coded strobing photography: Compressive sensing of high speed periodic videos." IEEE Trans. Pattern Analysis and Machine Intelligence, 33, no. 4 (2011): 671-686

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1.5. Definitions, acronyms and abbreviations

AES: Advanced Encryption Standard

ASI: Agenzia Spaziale Italiana

BPE: Bit-Plane Encoder

CCSDS: Consultative Committee for Space Data Systems

CS: Compressive Sensing

DWT: Discrete Wavelet Transform

ECSS: European Cooperation for Space Standardization

ESA: European Space Agency

FPA: Focal Plane Assembly

FWHM: Full Width at Half Max

GMES: Global Monitoring for Environment and Security

GSD: Ground Sampling Distance

HSI: Hyperspectral Imaging

HYP: Hyperspectral

MC: Matrix Completion

MDA: Maximum Data Amount

MMFU: Mass Memory and Formatting Unit

MSI: MultiSpectral Instrument

OZA: Observation Zenith Angle

PAN: Panchromatic

PHySIS: Sparse Signal Processing Technologies for HyperSpectral Imaging Systems

PRISMA: PRecursore IperSpettrale della Missione Applicativa

QoS: Quality-of-Service

SNR: Signal-to-Noise Ratio

SWIR: Short Wave Infra-Red

TT&C: Telemetry, Tracking and Command

VNIR: Visible and Near Infra-Red

w.r.t.: With respect to

2. Application scenarios and system requirements

The integrated HSI system to be designed and validated in the framework of the PHySIS project has to be defined according to precise requirements, architectural principles and specifications, which depend on the considered application scenario. Given that potential applications of a HYP acquisition system cover nowadays a wide range, the possibility to address their various distinct characteristics and needs within a single prototypical system is actually impractical. Furthermore, identifying specific application scenarios allows to steer the subsequent analyses and development activities, and to define drivers, constraints, and requirements for the final system.

Two main operational environments have been identified as the most relevant to be used as our main use cases, namely, i) spaceborne and ii) ground-based (terrestrial). The later can be further distinguished in a) indoor (i.e., in completely determined and stable acquisition conditions) and b) outdoor application scenarios.

This section provides a detailed description of the relevant application scenarios, for each one of the above use cases, where the PHySIS platform will apply to. In particular, it outlines the identified application scenarios, which are then transformed into traceable scenario requirements specifying the observational needs and quantitative system requirements for designing a complete prototypal system.

2.1. Spaceborne HSI platforms

The rapid development of sophisticated hyperspectral imagers has found a wide range of applications. Among them, satellite monitoring of natural resources and global land monitoring are of high significance with huge environmental, social and economic impacts. In addition, the design of spaceborne HSI systems is characterized by various challenges, which have not been efficiently resolved yet, including the capture, coding, restoration, and interpretation of hyperspectral image and video data for power constrained on-board systems.

2.1.1. Application scenario descriptions

In deliverable D2.1, several potential use cases of spaceborne HSI systems were overviewed and classified in distinct thematic areas, such as terrestrial ecosystems, aquatic ecosystems, atmospheric research, and natural resources, just to name a few. In all these cases, HSI can be exploited as a powerful analysis tool for applications in environment and ecology, aquaculture, forestry, agriculture, and geoscience [RD 12]. An advantage of HYP imagers when compared to typical broadband sensors is the ability to detect molecular absorption and particle scattering signatures of constituents. The finer spectral resolution of a HYP imager yields an enhanced performance in several tasks, such as the detection of surface materials and the inference of biological and chemical processes.

Concerning the spaceborne HSI application scenarios, we rely on two distinct satellite platforms, namely, i) PRISMA (PRecursore IperSpettrale della Missione Applicativa) [RD 13] and ii) Sentinel-2 [RD 14]. The choice of the former is motivated by the active involvement of PLANETEK, which enables access of the PHySIS consortium to the platform's architectural design details, as well as immediate access to the acquired HYP data. The choice of the later is prompted by the fact that it is an innovative European space programme, which will also support systematic and free access to high-resolution multispectral data to all users, including the general public, scientific, and commercial users. Furthermore, both satellite platforms are dedicated to Earth observation, which enables a more straightforward comparison of the associated scenario descriptions and system requirements, as well as of their performance against the PHySIS solution.

More specifically, the main objective of PRISMA is to develop a small mission for monitoring natural resources and characteristics of the atmosphere. On the other hand, Sentinel-2 is dedicated to monitoring of vegetation, soil, and water cover, as well as the observation of inland waterways and coastal areas.

Based on the above, the specific application scenarios, which will guide the testing and validation of a spaceborne HSI platform in the framework of PHySIS, are as follows: 1) land monitoring for a) agricultural (e.g., soil chemical composition) and b) forestry (e.g., tracking changes in natural or planted forest coverage) purposes; 2) soil mineral and texture monitoring; 3) coastal and inland waters monitoring. We emphasize here that, concerning the spaceborne application scenarios, the above two satellite missions will be used as benchmark systems to i) set the minimum hardware and software requirements (e.g., data acquisition, data compression ratios, transmission rates, etc.), and ii) provide real HYP/multispectral data, where the PHySIS architectural and algorithmic innovations will be applied to and compared against.

Each one of these application scenarios is characterized by distinct requirements dictated by the physical environment, resulting in a rigorous setting of the HSI system parameters [RD 15] [RD 16].

2.2. Scenario requirements

Measurement continuity and performance: Continuity of acquired data is required to guarantee effective exploitation of user investment, whereas any gap in data availability could jeopardize the provided Quality-of-Service (QoS). Furthermore, the reliability and performance of the provided services should be maintained. This implies that any modification or deviation from the predetermined technical specifications, such as spectral bands, spatial-spectral resolution, and data sampling, should be carefully analysed.

Revisit: In space application scenarios, the geometric revisit time represents the temporal periodicity of systematic acquisition of a given area disregarding cloud cover and under the same viewing direction. The effective revisit time represents the temporal frequency of systematic acquisition of a given area with cloud cover (excluding thin cirrus if thin cirrus clouds can be detected and their effect corrected) below a specified threshold and under the same viewing direction. Based on European cloud cover statistics, a ratio of 3 between the geometric and effective revisits is considered adequate.

Instantaneous coverage: The width of the swath depends on the specific application scenario (e.g., monitoring of vegetation properties, monitoring of floods and fire risk areas). In the context of instantaneous coverage, the influence of directionality on the observed reflectance should be minimized. For that purpose the observation zenith angle (OZA) should be kept below 15°.

Geographical coverage: It depends on the specific application scenario, and it can vary from a few tenths of km^2 up to a few hundreds of km^2.

Timeliness: Timeliness refers to the temporal span between data acquisition and product delivery to the end user. In space applications it usually varies from a couple of hours up to a day. Being in compliance with the required timeliness is essential to guarantee the increased performance of the provided services.

Table 1: Scenario requirements according to the specific spaceborne HSI application

	Agriculture	Forestry monitoring	Soil composition	Coastal & inland waters
Measurement continuity	min 5 days (plant growth varies but a minimum of 5 days suffices in most cases)	1-7 days	> 7 days	1-3 days
Revisit	4-5 days	4-5 days	4-5 days	4-5 days
Geographical coverage	Application dependent (few m^2 for local crops monitoring up to several km^2 for large region monitoring)	> 50 km	> 50 km	> 50 km
Timeliness	> 24 h	3 – 24 h	> 24 h	3 – 24 h

2.2.1. On-board system requirements of existing platforms

In this section, a detailed system description is given for both PRISMA and Sentinel-2, which comprise the benchmark platforms for guiding the design requirements and engineering aspects implementing the PHySIS HSI platform. The definition of the system requirements is based on the application scenario descriptions that were introduced in the previous section. The system requirements cover the end-to-end Earth observation system including high-level (hyperspectral/multispectral) instrument requirements, high data volume acquisition and handling, data compression, storage capacity, processing power, and downlink capabilities for transmission to ground control stations.

More specifically, the analytical parameters which define the system requirements, based on the above critical points, are as follows:

- Data acquisition and handling:
  - Sensor type
  - Number and distribution of spectral bands
  - Spatial resolution (Ground Sampling Distance (GSD))
  - Temporal resolution
  - Bus size
  - Quantization rate (in bits/pixel)
  - Signal-to-Noise Ratio (SNR)
- Data compression:
  - Compression ratio
  - Hardware requirements
  - Power consumption
- On-board storage:
  - Memory size
  - Data protection
  - Bus size
- Data transmission:
  - Transmission bandwidth
  - Downlink time per orbit
  - Power consumption

Technological analyses and developments consider as one of the fundamental drivers, their applicability in an operative spaceborne scenario. The data management capabilities represent a bottleneck in spaceborne systems, not only in terms of pure data acquisition (and on-board storage and processing), but also considering the huge amount of data to be downlinked to Earth. Thus, data compression in hyperspectral missions is actually mandatory. It is possible to obtain sensible telemetry gains by adding some complexity to the system. On the other hand this entails at the same time increasing the on-board consumption of power and processing resources and a trade-off between the different constraints has to be performed. Specifically, a practical scenario typically has an average information of 5 bits/pixel for lossless, 3 bits/pixel for near-lossless, and 1 bit/pixel for lossy compressions. Considering that most current detectors work with a 12 or 14 bit/pixel quantization, the needed compression ratios range from 2.4 to 14.

Flexible mini and micro-satellites equipped with high (spatial/spectral) resolution hyperspectral imaging sensors payloads, designed for Earth observation, represent the main use case. Specifically the ASI/PRISMA and the Sentinel-2 missions are being adopted as Earth-observation references. For the sake of clarity, a brief description of these missions and their relevant parameters are reported in the following.

2.3. PRISMA (HYP/PAN)

PRISMA is an Agenzia Spaziale Italiana's (ASI) mission, which is based on a hyperspectral/panchromatic (HYP/PAN) payload with spatial resolutions of 30 m and 5 m, respectively, a swath width of 30 km, a spectral range of 0.4 – 2.5 μm (HYP) with a continuous coverage of spectral ranges with 10 nm bands, and of 0.4 – 0.7 μm in panchromatic. Its main parameters are summarized in Table 2 - Table 5.

It should be noted that the amount of imaging that can physically be accomplished per orbit, based on the limitations of the sensor (and its ancillary equipment), is constrained by the:

- downlink data architecture and rates,
- number of ground receiving stations,
- actual on-board data compression rate,
- on-board mass memory storage unit,
- other variables of secondary importance.

The first assumption here is that the satellite has, on average, 4 contacts per day with the selected ground station, and that each one is about 9 minutes long, with effectiveness equal to 90% of the visibility time. This assumption actually leads to a total daily contact time of about 32 minutes.

A critical issue that can be immediately affected by the PHySIS application scenarios is the contextually limited allocation of downlink capability and the highly demanding hyperspectral imaging capacity. In fact, as derived from the ASI's X-Band ground station downlink facility, a daily effective downlink time of 32 minutes per day is available. This time yields up to 70 GB of data (HYP/PAN images) to be transmitted on a daily basis (from the coupled limitation of the downlink speed in X-Band and actual antennas visibility time).

Having fixed this value, the quantity expressed as maximum data amount (MDA) per day encompasses the fundamental need for high compression ratios achievable with the PHySIS novel signal processing approaches. Actually, this quantity demonstrates a typical HYP spaceborne imaging issue; it has often happened in the past that the high number of acquired bands cannot be actually down-streamed back to Earth. Considering the total volume of HYP data plus PAN data, which determines the system capacity to collect daily 108000 km^2, it is possible to determine the expected MDA per day. This is equivalent to acquiring 120 scenes/day, by assuming as a worst-case scenario that all of those scenes are HYP data. However, when the PAN data is acquired simultaneously with the HYP data, the total data volume capacity remains fixed and the equivalent area coverage is reduced correspondingly for the HYP data. Focusing on a single HYP scene, it is straightforward to evaluate pixels volume of a single image, which is equal to 256 Mpixel/scene. However, this depends on the HYP imaging sensor's swath width, GSD, number of bands, and quantisation bits (12 bits/pixel are used).

2.3.1. Image acquisition

PRISMA (PRecursore IperSpettrale della Missione Applicativa) is a mission lead by Agenzia Spaziale Italiana. It consists of a medium resolution hyperspectral imaging satellite aiming to provide global observation capabilities for the monitoring of natural resources and atmospheric characteristics, having Europe and the Mediterranean region as main area of interest. The PRISMA sensor is a hyperspectral instrument including a panchromatic camera at medium resolution, based on the pushbroom type observation concept providing 255 HYP and 1 PAN bands with spatial resolution of 30m and 5m respectively, a swath width of 30 km, a spectral range of 0.4 - 2.5 μm (400-1010 nm in VNIR range and 920-2505 nm in SWIR range) with a continuous coverage of spectral ranges with 12 nm bands, and of 0.4 - 0.7 μm in panchromatic. The observation data are digitized on 12 bit.

Table 2: Data acquisition

Sensor	Type	Swath	Bands
	HYP/PAN push-broom	30 Km	257 (256 HYP, 1 PAN)
Number and distribution of spectral bands (nm)	HYP		PAN
	VNIR: 400 – 1010 SWIR: 920 – 2505 Resolution: 12 nm		400 – 700 Resolution: 12 nm
Spatial resolution (GSD)	HYP: 30 m PAN: 5 m		
Temporal resolution	15 Orbits per day		
Daily imaging capacity	108000 km²/day		
Quantization (bits/pixel)	12		
SNR	HYP		PAN
	VNIR: > 500 (650 nm) SWIR: > 400 (1550 nm) > 200 (2100 nm)		> 240

2.3.2. On-board storage

Considering the total volume of HYP data plus PAN data that sets the system capacity to collect daily 108000 km², it is possible to determine the expected maximum data amount per day. This is equivalent to the acquisition of 120 scenes/day, assuming as worst-case scenario that all of them are HYP data. In a single HYP scene pixel's volume of a single image is equal to 256 Mpixel/scene. This piece of information comes from the HYP Imaging sensor's characteristics: swath width, ground sampling distance and number of bands. The maximum amount of HYP data acquired daily can be evaluated applying the 12-bit signal quantization to pixels volumes per scene (i.e. less than 400 MB/scene) and then multiplying it for the 120 scenes/day mission target. The available on board memory is 32 GB and according to downlink opportunities it is not always large enough w.r.t. acquisition capability.

Table 3: Data compression & on-board storage

Compression ratio	N/A
Compression method	N/A
Data amount per day	70 GB
Storage capacity	256 GB
Input data rate	600 Mbit/s
Output data rate	N/A
Bit error rate (BER) per day	N/A
Encryption standard	N/A
Maximum data amount per day	43 GB

2.3.3. Transmission to ground stations

The PRISMA satellite has, on average, four contacts per day with the ASI's X-Band ground station. Each one is about nine minutes long and has an effectiveness equal to 90% of the visibility time: this actually leads to a total daily contact time of about 32 minutes. The satellite has two communication links: one in S band with the Fucino ground station, providing telemetry and telecommands for satellite management, and one in *X* band with the Matera ground station providing telemetry link for image data download. Considering the *X* band link bandwidth, the 32 minutes are equivalent to a 70 GB data volume, which is smaller than the actual on board possible production rate. So a critical point to be considered is the limited allocation of downlink capability versus the highly demanding hyperspectral imaging needs.

Table 4: Data transmission

Transmission modes and rates	300 Mbit/s [2]
Downlink time per day	32 minutes
Transmission size per orbit	max 43 GB (per day)
Data amount per day	70 GB

2.3.4. Instrument dimensions and power requirements

The overall dimensioning and architectural design of the PRISMA are shown in Figure 1 where we can identify the key components, namely, the payload, the solar array, the communications antenna, the electronics modules, and the power module. The specifications are given in Table 5.

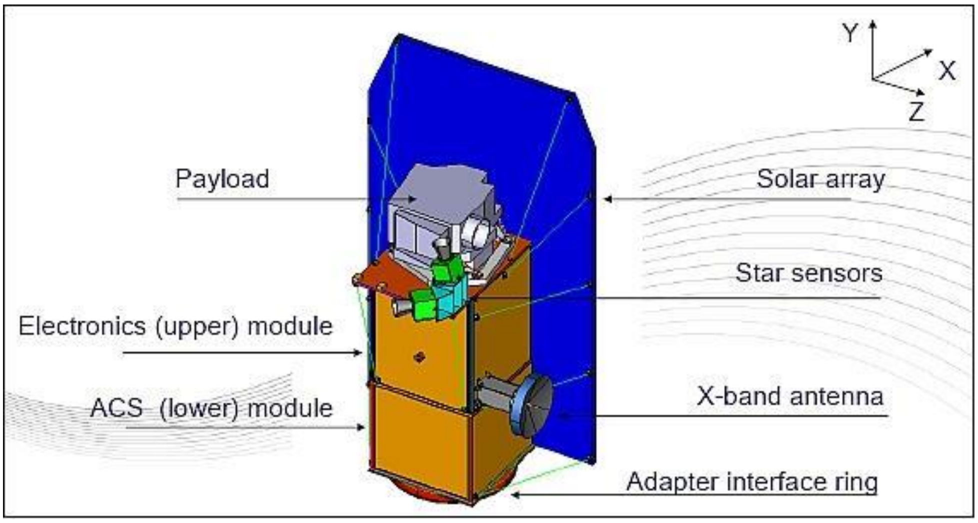


Figure 1 : CAD model of PRISMA.

[2] Note (*): only direct downlink to ground stations, not considering the European Data Relay Satellite

Table 5: Instrument dimension and power requirements for PRISMA

Optical head dimension	700 mm width 700 mm depth 1100 mm Nadir
Main electronics box dimension	400 x 300 x 250 mm
Optical head mass	< 80 Kg
Main electronics box mass	< 8 Kg
Power consumption	< 60 W in Acquisition Mode < 40 W in Standby Mode

2.4. SENTINEL-2 (MSI)

Sentinel-2 is dedicated to Europe's Copernicus programme, whose Global Monitoring for Environment and Security (GMES) mission is to support operational applications primarily for land services, including the monitoring of vegetation, soil and water cover, and the observation of inland waters and coastal areas, as well as for atmospheric correction and cloud/snow separation. The mission is based on a constellation of two identical satellites in the same orbit (180° apart for optimal coverage and data delivery) Sentinel-2A and Sentinel-2B, launched separately (the former is scheduled in June 2015, while the later in the second half of 2016).

Regarding the RF communications module, it consists of an X-band payload data downlink at 560 Mbit/s and S-band Telemetry, Tracking and Command (TT&C) data link (64 Kbit/s uplink, 2 Mbit/s downlink) with authenticated/encrypted commands. Furthermore, in order to support continuous data transmission to ground control stations, an optical laser link is also employed to relay the image data to geostationary satellites.

2.4.1. Image acquisition

Each of the Sentinel-2 satellites carries a single payload, namely, a MultiSpectral Instrument (MSI), which is based on a push-broom concept. A push-broom sensor works by collecting rows of image data across an orbital swath width of 290 km and exploits the forward motion of the spacecraft along the path of the orbit to provide new rows for acquisition. The light, which is reflected to the MSI from the Earth and its atmosphere, is collected by a three-mirror telescope and focused, via a beam-splitter, onto two Focal Plane Assemblies (FPAs): one for the 10 visible and near-infrared (VNIR) wavelengths and one for the 3 short wave infrared (SWIR) wavelengths. The spatial resolution varies among 10 m (4 bands), 20 m (6 bands) and 60 m (3 bands). The 4 bands at 10 m resolution ensure continuity with missions such as SPOT-5 or Landsat-8 and address user requirements, in particular, for basic land-cover classification. The 6 bands at 20 m resolution satisfy requirements for enhanced land-cover classification and for the retrieval of geophysical parameters. Bands at 60 m are dedicated mainly to atmospheric corrections and cirrus-cloud screening.

The radiometric resolution, which measures the ability of an imaging system to record different levels of brightness or tone, is 12-bit giving a potential range of brightness (quantisation) levels from 0 – 4095. The average observation time per orbit is 16.3 minutes, while the peak value is 31 minutes (duty cycle of 16-31%). The raw image data are either left in its raw format or compressed using lossless and lossy compression based on reversible JPEG2000 and standard JPEG2000 [RD 17], respectively. Besides, the upper-left pixel corner coordinates of all bands shall have the same coordinates and shall be a multiple of 60m. As an example, the volume for an image of 290km x 290km is approximately 2,3GB for lossy and 3,3GB for lossless compression, yielding an expected data rate of 450 Mbit/s (after compression) based on high spectral efficiency modulation (8PSK). In addition, the MSI instrument can be configured to have data in compressed (nominal case) or by-passed/uncompressed (calibration or contingency acquisition case). The later, by-passed/uncompressed mode implies that data from only a subset of the detectors are provided.

Table 6: Data acquisition

Sensor	**Type**		**Swath (km)**			**Bands**	
	MSI push-broom		290			13 (10 VNIR, 3 SWIR)	
Distribution of spectral bands (nm) (Central wavelength (bandwidth))	1	2	3	4	5	6	7
	443 (20)	490 (65)	560 (35)	665 (30)	705 (15)	740 (15)	783 (20)
	8	8a	9	10	11	12	
	842 (115)	865 (20)	945 (20)	1380 (30)	1610 (90)	2190 (180)	
Resolution (GSD)	10 m		20 m			60 m	
	Band No. {2, 3, 4, 8}		Band No. {5, 6, 7, 8a, 11, 12}			Band No. {1, 9, 10}	
Temporal resolution	5 days (equator, cloud-free conditions)						
Size	~290 kg						
Power	< 266 W						
Quantization (bits/pixel)	12						
SNR	50 (Band 10) – 172 (Band 8) (depends on the spectral band and its corresponding reference radiance)						

2.4.2. On-board storage

The combination of the large swath (290 km), spectral range (13 bands from the visible to the short-wave infrared), spatial resolution (10/20/60 m), coupled with the global and continuous acquisition requirement with high-revisit frequency, leads to the daily generation of 1.6 TB of compressed raw image data from the 2-satellite constellation. This corresponds to an average continuously sustained raw-data supply rate of 160 Mbps (compressed).

Concerning the on-board data storage capacity, it employs a 6 TB Mass Memory and Formatting Unit (MMFU), with an input data rate of 490 Mbit/s, based on NAND-flash technology as baseline, which supplies the mission data frames to the communication subsystems. The MMFU instrument mass and size equal to 14 kg and L: 302 x W: 345 x

H: 240 mm, respectively, with a maximum power consumption of 54 W for simultaneous data record and replay.

Table 7: Data compression

Compression ratio	Between 2 and 3 (fine-tuned for each spectral band)
Compression method	Lossy wavelet transform (JPEG2000) (Tile size: 1024x1024, Flush period: 1024 lines, Codeblock size: 64, Decomposition levels: 5)
Storage capacity	6 Tbit (Beginning-of-Life (BoL), Astrium NAND-flash) 3 memory modules
Input data rate	490 Mbit/s + 80 Kbit/s (housekeeping)
Output data rate	2 x 280 Mbit/s (downlink)
Bit error rate (BER) per day	5.9×10^{-14}
Memory organization	Packet stores – ESA EO architecture (HK, Ancillary data, Image data) Re-configuration of packet size via TT&C Re-transmission (Re-Tx) of missing data is enabled (real-time Re-Tx requests are not currently possible)
Encryption standard	N/A
Bus size	< 15 kg
Power	< 54 W (Record & Replay) < 29 W (0 W at BoL) (Data retention)

2.4.3. Transmission to ground stations

Sentinel-2 satellites have high bandwidth needs as well, but can rely on a wider down-link system. Data acquired are sent to ground and received at the four X-band core stations or can be either transmitted via laser-link to the European Data Relay System (EDRS), which relays data via geostationary satellites to ground where they are received at the user Ka-band stations. Use of EDRS is particularly useful when satellite is not within range of the X-band ground stations, allowing information to be even more readily available to end users. Sentinel applies a lossless compression scheme on board, allowing to reduce the 1.3 Gbps data flow to 450 Mbps.

Table 8: Data transmission

Transmission modes and rates	X-band (scientific data downlink): 560 Mbit/s
	Laser communication link via EDRS (data relay to geostationary satellites): LEO-to-GEO:2.8 Gbit/s (1.8 Gbit/s user data) GEO-to-ground: 600 Mbit/s Ka-band (Under development: optical ground station LEO-to-ground: 5.625 Gbit/s GEO-to-ground: 2.8 Gbit/s)
	S-band (TT&C data): 64 Kbit/s uplink, 2 Mbit/s downlink
Transmission policy	Tx via X-band and optical laser link Re-Tx requests via S-band (not in real time)
Transmission size per orbit	max 1.6 TB

2.5. Terrestrial HSI platforms

This section provides the scenario descriptions and system requirements for a terrestrial HSI platform. PHySIS will consider problems related to terrestrial applications, such as the spectral classification of objects and the detection of malformation in products. The requirements for this class of applications include

- Spectral characterisation of the object of interest
- The spatial, spectral and temporal resolution required for achieving the objectives
- Collection of a sufficiently large number of examples that will be used as training and validation data.

We consider an example application scenario from the recycling industry, where HSI can be instrumental in the automation of the process that could lead to a dramatic improvement in performance. More specifically, concerning the case of terrestrial application scenarios, the outcome of the PHySIS project could be exploited in the recycling industry, whose high environmental and economic impacts are well recognized. Recycling is a key component of modern waste reduction and is the third component of the "Reduce, Reuse and Recycle" waste hierarchy. It aims at preventing waste of potentially useful materials, restricting the consumption of raw materials and energy usage, reducing air and water pollution from incineration and landfilling, respectively, as well as lowering greenhouse gas emissions as compared to plastic production.

Hyperspectral imaging technology can utilize the invisible part of light in the near infrared (NIR) wavelength region to analyse the chemical footprint of goods and materials and perform the so called chemical imaging, that is, the representation of objects in artificial colour according to their chemical composition.

In the framework of PHySIS, the developed HSI platform could be incorporated into existing equipment, and for all steps in the process chain, of sorting systems in order to increase their efficiency in discriminating and classifying accurately the various objects on the conveyor belt. Most importantly, such a platform could act in a non-contact and non-destructive way for isolating dangerous toxic wastes without human intervention. The generic structure of such a sorting system is shown in Figure 2.

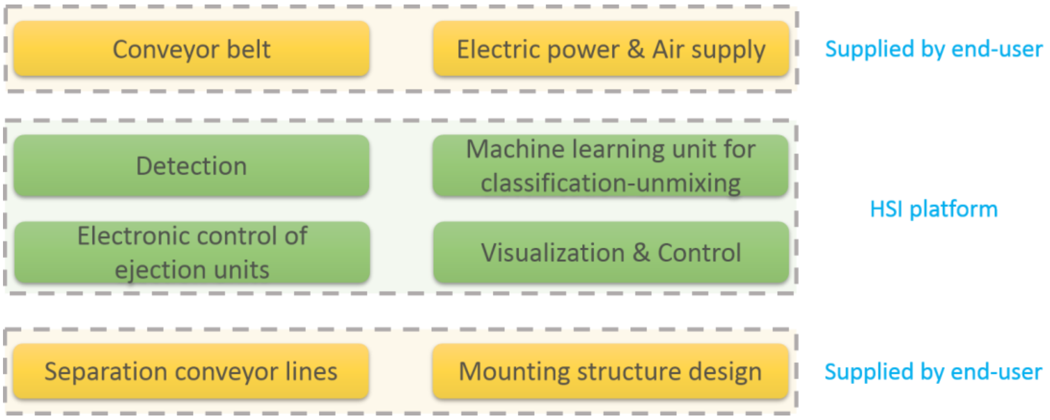


Figure 2: Generic structure of an HSI-based sorting system

Concerning the HSI unit, we start with the data acquisition process followed by a training phase, where the reference spectra are assigned to artificial colours. With respect to the specifications of the HSI sensing device, we use the HELIOS Core system as a benchmark, which is used in existing industrial linescan sorting systems. This system performs hyperspectral classification and sorting in the VIS/NIR, NIR or SWIR (each spectral range is supported by a distinct product) by acquiring complete spectral images line by line for each local pixel in parallel. The classification and sorting parameters can be adapted to the end-user's specific application requirements. Table 9 : Specifications of HSI platform for sorting systems in the recycling industry summarizes the main specifications of such an HSI platform for sorting systems in recycling materials of broad usage, such as plastic (e.g., PVC, PET, TETRA-PACK), paper, and aluminium.

Table 9 : Specifications of HSI platform for sorting systems in the recycling industry

	VIS/NIR	NIR	SWIR
Spectral range	0.4 – 1.0 µm	1.1 – 1.7 µm/0.9 – 1.7 µm	1.4 – 2.4 µm/1.3 – 2.3 µm
Line scan rate	330 Hz (full frame)	330 Hz (full frame)	100 Hz (full frame)
Spectral resolution	9 nm @ 30 µm slit		
Spectral sampling	1.9 nm	1.9/2.5 nm	3.2 nm
Pixel resolution (sensor)	320 (spectral) x 256 (spatial)		
Pixel size	7 x 7 µm	30 x 30 µm	30 x 30 µm
Data depth	12-bit		
Data processing	On-board, FPGA		
Dimensions	330 x 190 x 160 mm (without lens), ~10 kg	330 x 190 x 160 mm (without lens), ~10 kg	595 x 300 x 155 mm (without lens), ~18 kg
Power consumption	1.5 A	2.5 A	7 A

3. The PHySIS platform for spaceborne applications

This section gives the details related to the design principles of our proposed PHySIS platform, simulating a spaceborne application scenario. More specifically, based on the specifications and system requirements, as described in the previous sections, we now analyse all the relevant factors of the PHySIS HSI system in order to satisfy these requirements both on-board and at ground stations. For the on-board case, such factors include a) IMEC's imaging sensors characteristics for data acquisition, b) process for satellite data compression, and c) satellite data transmission (channel coding). Concerning the ground-based stations, we describe the requirements for achieving a) improved HYP image enhancement and restoration performance (e.g., in terms of SNR enhancement rate (denoising, deblurring), spatio-spectral super-resolution rate, processing speed and hardware requirements), and b) improved image understanding (e.g., by employing ground-truth validation, fusion of multiple data, and temporal resolution processing).

3.1. PHySIS HSI satellite data acquisition

The core of a hyperspectral camera is a spectral unit, which is an optical component that splits the light into its separate wavelengths. The PHySIS platform will utilize the knowhow of IMEC which has been investigating various approaches in integrating the filters directly on top of the imagers at wafer level and remove the requirements of discrete optical components, complicated system assembly and alignment issues, thus enabling a solution that is scalable to volume applications.

The radiation of the ground sample cells in the scene (illuminated by the sunlight) enters the slit of the instrument after passing through the telescope. The slit acts as a field stop to determine the instantaneous FOV in spatial directions to Dx by Dx is the length of a cross-track line in the satellite flight direction (also called the along-track direction), and the y is the width of the cross-track line (also called the swath). The radiation from the slit is collimated by either a lens or a mirror and then dispersed by a dispersing element, which is typically a grating or prism The grating disperses the radiation so that the propagation direction of the radiation of each ground sample cell depends on its wavelength. The dispersed radiation of each ground sample cell is then focused on the image plane (called the focal plane) by the focusing optics. A ground sample cell in the cross-track line is presented on the image plane by a series of monochromatic components distributed among all of the detector elements of row D (the highlighted row of the detector array in Figure 3) in the spectral direction This row of monochromatic components forms a continuous spectrum (a spectral curve) of the ground sample cell D. The radiation is detected by a 2D detector array, such as a CCD or CMOS detector. In this way, a 2D focal image is formed at a moment when the satellite "looks" at one line ground scene. One dimension of the focal image corresponds to the spatial direction of the cross-track line on the ground; another dimension corresponds to the spectral direction that is the extension of the spectrum of the ground sample cells. Another spatial dimension of a scene is obtained by the flight of the satellite in the along-track direction. More focal images are generated by the satellite flight in the along-track direction.

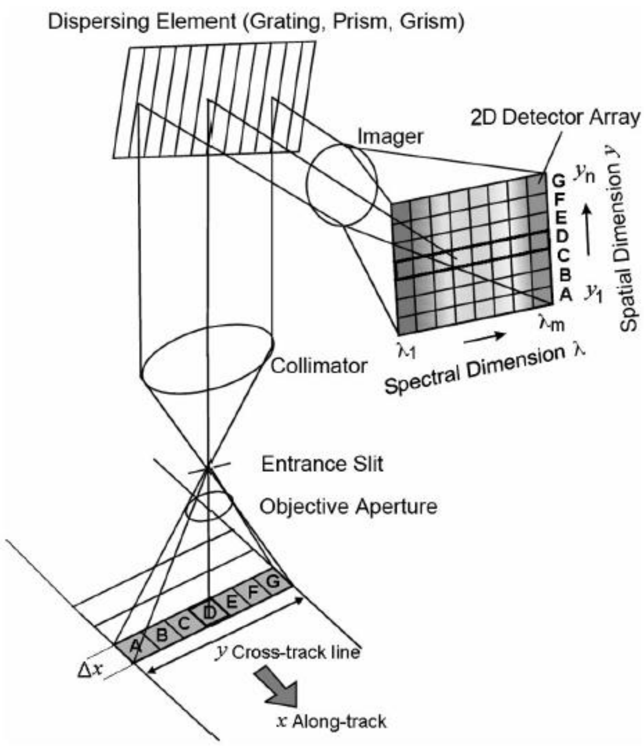
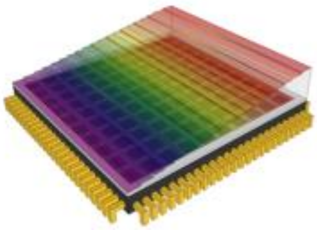


Figure 3: Operational principles of push-broom HSI satellite imaging

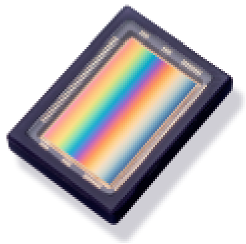
Unlike grating or linear filters, IMEC's snapshot imagers employ spectral filter designs based on the Fabry-Pérot principle, which enables the design and fabrication of ranges of optimized filters at various wavelengths with flexible/customizable layout and customizable spectral bandwidth, while leading to a reduction in the number of discrete and bulky optical components needed, which results in more cost-effective and compact imaging systems. The developed imagers are compact and fast, utilizing the low-cost CMOS process technology which has been demonstrated in two specific instances, namely a linescanner and a mosaic based snap-shot imager.

Linescan Hyperspectral Sensor

In the linescan architecture (cf. *Figure 4*(a)), the filters are arranged in a staircase-like structure over the pixel array. Such a design is useful in applications where the scene of interest has a natural translation movement (e.g., in a conveyor belt) and the hyperspectral imager is used as a line-scanner.



(a)



(b)

Figure 4: (a) concept of wedge layout (filter heights exaggerated for illustration) (b) a packaged wedge based hyperspectral imager

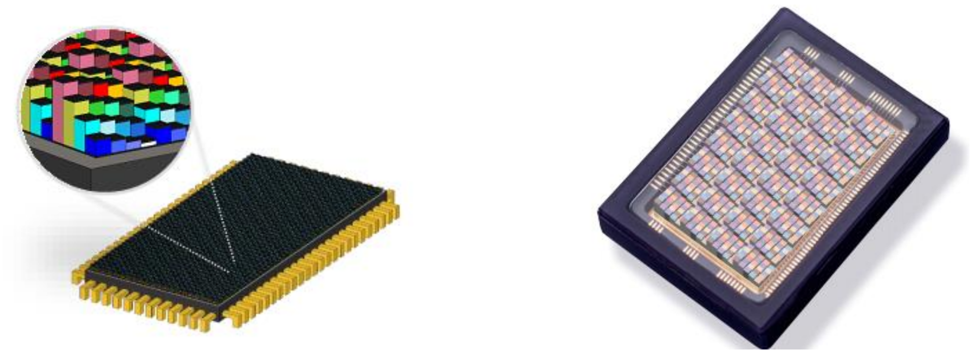
Table 10: Key specifications of wedge-based spectral imager

Spectral range	600-1000nm
Number of spectral bands	100
FWHM	< 10nm, using collimated light
Filter transmission efficiency	~ 85%
Imager	CMOSIS CMOS CMV 2000 imager
Number of lines/ spectral band	8
Number of spatial pixels/line	2048

Scan rate in number of lines/sec	2880
Pixel pitch	5.5 μm
Bit depth	8 / 10 bits

Mosaic Hyperspectral Sensor

An alternative design is a mosaic architecture which is useful in applications where the scene of interest has objects which are static or have random movements or in cases that require snapshot video acquisition. The linescan architecture enables the acquisition of hyperspectral images with high spectral and spatial resolution, while mosaic architecture inherently dictates a trade-off between spectral and spatial resolution.



(a) (b)

Figure 5: (a) concept of mosaic layout (filter heights exaggerated for illustration) (b) a packaged tile based hyperspectral imager.

Within PHySIS, we will explore techniques for increasing the spectral resolution of the sampled hypercubes by means of novel signal processing tools including Matrix Completion and Compressed Sensing. More specifically, we will investigate the problem of demosaicing hyperspectral image cubes sampled by SSI cameras by formulating the estimation of the HSI data as the recovery of undersampled low-rank matrices. The formulation according to the MC framework is well suited for this specific problem since the existing strong spatial and spectral correlations can provide critical information for the recovery of the missing spectral profiles. An important benefit of the proposed formulation is the precise control over the spatial and spectral resolution by appropriate grouping of pixels.

In addition to the application of novel signal processing algorithms on the prototypical systems developed by IMEC, we will also consider extensions of these schemes that will utilize additional hardware in order to encode even more information during image and video acquisition. Examples of such hardware include active lighting elements, coded apertures, dispersive elements and optical duplicators placed in front of the multispectral filter array and the detectors. The objective in this case is to offer a new set of possibilities, including the ability to extract depth information, where the necessary cues for estimating distance can be extracted from the spectral characteristics of the recorded scenes. Overall, the envisioned HSI system that will be designed and developed within the PHySIS project will consider HYP imagers designed by IMEC.

Table 11: Key specifications of mosaic-based spectral imager

Spectral range	470-630nm/ 600-1000nm
Number of spectral bands	16/25
FWHM	< 10nm, using collimated light
Filter transmission efficiency	~ 85%
Imager	CMOSIS CMOS CMV 2000 imager
Imager resolution	2Mpixel
Resolution per tile/band	512 x 272 pixels/ 409 x 216 pixels
Frame rate in number of hypercubes/sec	340
Pixel pitch	5.5 μm
Bit depth	8 / 10 bits

Imaging Sensor

All the hyperspectral sensors are based on CMOSIS CMV2000 sensors, which have the underlying performance characteristics shown in *Table 12*.

Table 12: Specifications of the imaging sensor

Sensor spatial resolution	2048 x 1088 pixels (~ 2MPixels) (Global Shutter)
Pixel size	5,5 µm x 5,5 µm
Full well charge	13,5 Ke-
Conversion gain	0,075 LSB/e- (10-bit mode)
Sensitivity	4,64 V/lux.s
Temporal noise	13 e- (RMS)
Dynamic range	60 dB
Optical format	2/3”
Parasitic light sensitivity	< 1/50000
Dark current	125 LSB/s (@25°C)
Operating temperature	-30°C to +70°C
Power consumption	600 mW
Fixed pattern noise	< 1 LSB (<0,1% of full swing)

HSI Camera System

The above sensors are integrated into Ximea XiQ USB3 cameras. The Ximea cameras have the following properties.

Frame rates	Upto 170 fps For linescan translates to up to 1360 lines/sec For snapshot mosaic up to 170 hypercubes/sec
Image data interface	USB 3.0
Power requirements	1.6W
Lens mount	C or CS Mount (e.g. Edmund optics 35mm fixed focal length VISNIR lens)
Weight	~ 31 grams
Dimensions WxHxD	26 x 26 x 30 mm

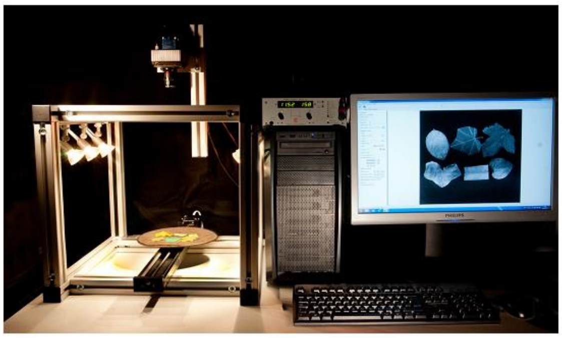
The HIS detectors are housed in a compact Ximea camera platform which is shown in *Figure 6*.

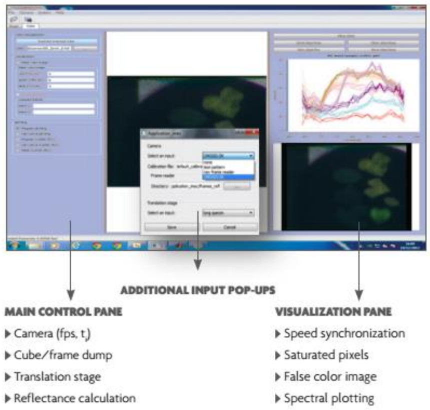
Figure 6: Complete HSI camera system by Ximea

IMEC HSI Evaluation System

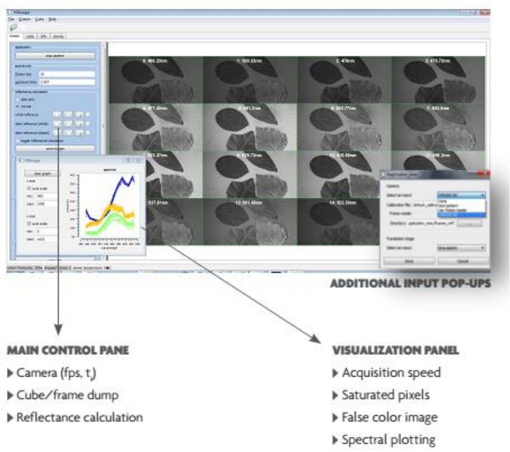
The above sensor and camera will be integrated into an evaluation kit. The purpose of the evaluation kit is to provide a solution to capture and store hyperspectral data cubes. The data can be stored in ENVI compatible data format (and also other formats like BIL/BSQ/PNG).

Linescan Evaluation System: includes illumination, translation stage, a cube-frame, power supplies, 35-mm VISNIR C-mount lens, and white reflectance tiles. The acquisition software can perform basic functions like (exposure control, reflectance calculation, speed synchronization and visualization).





Snapshot Evaluation System: includes illumination, stage, a cube-frame, power supplies, 35-mm VISNIR C-mount lens, and white reflectance tiles. The acquisition software can perform basic functions like (exposure control, reflectance calculation and visualization).



3.2. CS-enabled acquisition with IMEC mosaic HSI camera

In addition to demosaicing, we will also consider the introduction of a coding mask in order to perform incoherent sampling and achieve higher quality reconstruction based on the framework of Compressed Sensing (CS). CS imposes two necessary conditions for efficient sampling and reconstruction of the data: (a) the *sparsity* of the signals when represented in an appropriate basis and (b) the *incoherence* of the sampling process. Regarding the signal sparsity, natural scenes imaged by consumer and specialty cameras have been shown to have a sparse representation in an appropriate domain, like the wavelet domain, due to inherent spatial correlations. To perform incoherence sampling, CS imaging systems employ some form of multiplexing of the incoming light, in order to encode the high dimensional data into compressive measurements. Then, reconstruction of the complete image in achieved by solving either a convex or a greedy numerical optimization problem. Coded imaging can be employed in order to support:

- Spatial resolution enhancement

Increasing the spatial resolution of the acquired imagery is very important given the typical low resolution multispectral sensors. For example, although the IMEC mosaic camera supports 2Mpixel imaging, in order to provide multispectral imagery, binding of pixels must considered. The IMEC camera can support *4x4* and *5x5* binding modes in order to provide 16 and 25 spectral bands respectively. As a consequence of the binding operation, the effective spatial resolution per band is reduced by a factor of 16 and 25 respectively, relying on demosaicing for interpolation of the unavailable measurements.

In order to introduce the CS paradigm for spatial resolution enhancement, the designer must formally introduce a method for *spatial multiplexing*. Spatial multiplexing refers to the design philosophy where the main objective is to enhance the spatial resolution of the imaging system. The motivation for introducing spatial multiplexing is grounded on the need to acquire imagery of higher spatial resolution than the resolution offered by the imaging sensor. The need is fuelled by the high cost, size and complexity associated with the introduction of a large number of sensor elements, especially when such sensors must operate in challenging regions of the EM spectrum. One of the most prominent examples of spatial multiplexing based CS is the Single-Pixel Camera, which can acquire and reconstruct images of relatively high spatial resolution from a single sensor [RD 26].

A key design choice for a CS-based optical imaging architecture is related to the technologies that will be used for optically modulating the incident light field before acquisition. Optical modulation technologies, primarily include Structured Light Modulators (SLMs), Digital Micromirror Devices (DMDs), Coded Apertures (CAs), Coding Masks (CMs), Electronically Tunable Wavelength Filters (ETWFs) and Lenslet Arrays (LAs) [RD 25].

SLMs in general are devices that can control the amplitude, phase and polarization of light in space and time. SLM can be broadly divided into two classes, namely optical MEMS such as DMDs, which employ electro-mechanical control of components to modulate light, and Liquid Crystal based approaches such as Liquid Crystal on Silicon (LCoS) which control the amplitude and the phase of the reflected or transmitted light by electronically controlling the states of the liquid crystals.

The DMD technology is an example of a Micro-Electro-Mechanical System (MEMS) where an array of individually addressable mechanical micromirror is set to either one of two states, corresponding to a specific tilt range. TI DMDs are among the most established systems and currently available systems feature up to 4MPixel mirror arrays on a 13.68 μm pitch. DMDs have been explored for imaging applications as a way of controlling the projection of coloured illumination, volumetric displays, scanning microscopy and spectroscopy among others.

DMDs has been extensively explored in the context of CS for achieving spatial and temporal multiplexing of light fields, while an added benefit of DMD technology is that it has been recently proven as a space-worthy component, tolerating the challenging conditions of space [RD 24].

FORTH is equipped with a TI DLP® LightCrafter™ Evaluation Module which contains a DMD subsystem, in addition to a light projection subsystem, composed of low resolution 608 x 684 micromirrors, supporting up to 4KHz binary patterns and 120Hz 8-bit patterns. This subsystem can be used as a spatial resolution enhancement component in conjunction to the IMEC HSI cameras.

- Temporal resolution enhancement

Temporal resolution refers to the number of hypercubes that be acquired during a given time period. For the IMEC mosaic camera, the temporal resolution is up 170 hypercubes per second. This is a relatively high temporal resolution, sufficient for most terrestrial applications. For space applications however, the motion of the camera due to the motion of the platform can lead to blurring and cross-talk between different spatial locations. Similar to the case of spatial resolution enhancement, temporal resolution can be achieved by introducing temporal multiplexing.

In *temporal multiplexing*, the key requirement is high frame rate acquisition, a requirement often found in ranging and 3D imaging architectures such as LIDAR imagers where high temporal resolution is required. Temporal multiplexing can be introduced through the use of Coded Shutters. Coded Shutter, also known as Flutter Shutters, imaging can achieve temporal super-resolution and reduce motion blur of video sequences by controlling the behaviour of a global camera shutter. This idea was incorporated with CS based sampling and reconstruction architectures to allow recovery of high speed phenomena, much higher than the actual camera frame-rate [RD 22]. Electronically controlling per-pixel shutter has also been explored in the context of CS imaging [RD 23], however, controlling individual pixel exposures is a technology that not readily available.

- Spectral resolution

Spectral resolution represents both the number of spectral bands acquired during each frame as well as the radiometric resolution which refers to the number of bits that are allocated for each measurement. Increasing either one can have a very positive effect on the quality of the acquired data and the discrimination capabilities between different samples (e.g., material, functional conditions etc.).

Regarding the radiometric resolution, the imaging architecture parameters that controls this aspect are i) the encoding bit rate of the ADC and ii) the settings for measurements quantization introduced for storage and transmission. While the ADC rate is hardware dependent, the quantization quality is software controlled. As a result, we will explore recovering measurements that have been affected by quantization-type noise.

3.2.1. Hyperspectral light field acquisition

In addition to the previous examples of imaging resolution, CS can also be instrumental in supporting novel imaging capabilities that are available through typical imaging architectures. One such example is the ability to acquire light fields instead of the single-valued spatial distribution of intensity. Light fields encode the direction, in addition to the spatial distribution of the intensities, of the light rays reaching the detector. As a result, light field camera can provide 3D information by encoding depth-related light information through the encoding of the angular distribution of the light rays.

An example of a proposed architecture that can achieve Hyperspectral Light Field acquisition is shown in Figure 7. The prototypical design consists of three parts:

- Focusing lens: the focusing lens are introduced in order to focus the incoming light from infinity to the focal plane of the imaging system. Depending on the scenario, i.e. different distances from the ground, different lens architectures are required. In satellite imaging, typically a Cassegrain architecture is employed for focusing the light reflected from Earth's surface. In any case, complex optical focusing architectures can be reliably modeled by a single lens of equivalent optical power.

- Coding mask: the role of the coding is to perform spatial and temporal multiplexing of the incoming light. Spatial multiplexing is achieved when the resolution of the coding mask is different than the resolution of the detector array, while temporal multiplexing is achieve by allowing the dynamic adjustment of the coding pattern, through the use of a SLM system like a LcoS.

- The imaging detector follows the IMEC mosaic architecture where the spectral filters are deposited on top of the imaging pixels, effectively associating each pixel with a specific spectral region.

Depending on the requirements, one must select the appropriate optical modulation component. On the one hand, when the imaging architecture equipped with a DMD can achieve temporal multiplexing thus supporting high frame rate acquisition, while on the other hand, introducing CA can support the spatial resolution enhancement. Note that based on the current fabrication process, spectral multiplexing is a more challenging case. Recovery of the acquired imagery will be achieved by considering the sparse minimization of the acquired measurements on an overcomplete dictionary.

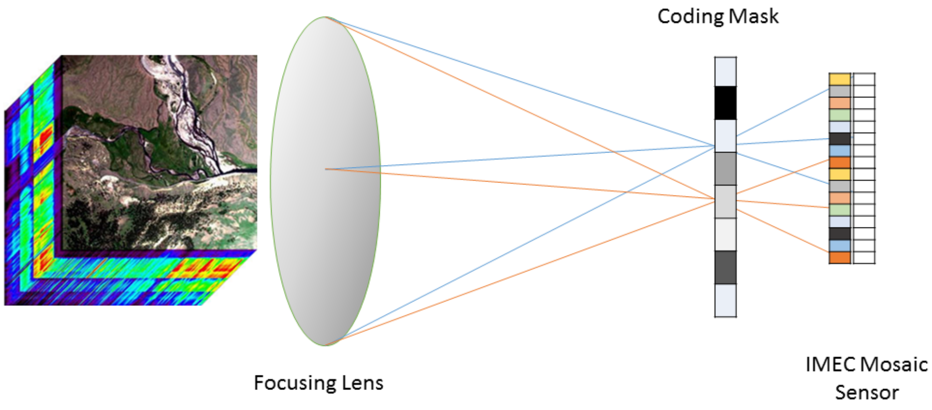


Figure 7: CS-enabled SSI acquisition using IMEC Mosaic Sensor

3.3. PHySIS HSI satellite data compression

The proposed HYP image data compression scheme to be developed in the framework of PHySIS will be in compliance with the recommended standard [RD 03] for image data compression, which is applicable to a wide range of spaceborne digital data, as it has been approved by the Consultative Committee for Space Data Systems (CCSDS). This standard establishes the recommended data structures and algorithms for compressing two-dimensional (2-D) digital spatial image data from payload instruments, and specifies how this compressed data shall be formatted into appropriate segments to enable decompression at the receiver. We emphasize at this point that our compatibility will be related to data formatting and packetization issues, whereas concerning the compression algorithm, a completely novel solution will be developed in the framework of PHySIS exploiting the power of compressive sensing (CS) and matrix completion (MC) technologies, which will replace the suggested image compression scheme based on the discrete wavelet transform (DWT).

Source coding for data compression is commonly utilized in data systems to reduce the volume of the acquired raw data in order to address issues including a) reduction of transmission channel bandwidth, b) reduction of buffering and storage requirement, and c) reduction of data transmission time at a given rate.

3.3.1. Bit-based conventions

Before proceeding, we briefly overview the conventions to be followed for the design of the PHySIS HSI platform, with respect to the enumeration of bits. Regarding the specification of headers for compressed data, this enumeration scheme is shown in [RD 04]. When an N-bit word is used to express an unsigned binary value (e.g., a counter), the Most Significant Bit (MSB) will correspond to the highest power of two, that is, 2^{N-1}. We note here that, in general, a different bit numbering convention can be used to index magnitude bits in the generated CS measurements, analogously to the different numbering convention that is used to index magnitude bits in the DWT coefficients as described in [RD 03]. Furthermore, in accordance with the modern data communications practice, satellite data are usually grouped into 8-bit “words” (bytes), which conform to the above convention.

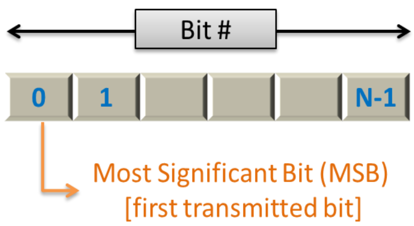


Figure 8: Enumeration of bits in the specification of headers for compressed data

3.3.2. Data compression modes

In order to support several distinct types of HSI instruments, two different classes of data compression methods should be supported, namely, *lossless* and *lossy*. In the former case, the original data can be reproduced exactly, whereas in the latter case, quantization or other approximations used in the compression process result in some distortion in the reconstructed data. For instance, the available storage capacity affects the choice among the two classes, since the increased information content of data subjected to lossless compression yields a larger volume of compressed data.

The targeted properties for guaranteeing an increased performance of the designed HYP image data compression scheme should be as follows:

- support high-rate HYP/MSI instruments used on-board of satellites,
- control the trade-off between compression performance and complexity,

- support fast and low-power hardware implementation through a compression scheme of reduced complexity,
- focus on simplicity of implementation by supporting a limited set of key options, without requiring in-depth algorithmic understanding.

The generic form of the data compression module is shown in Figure 9. In particular, it consists of two distinct sub-modules, namely, the *dimensionality reduction* part and the *encoder*. Furthermore, the HSI compression module should support both *frame-based* input formats (e.g., image frames captured by a CCD array) and *strip-based* input formats (e.g., image stripmaps captured by a push-broom HSI sensor). An image pixel dynamic range has also to be specified, with a value of 16 bits being a commonly adopted choice. The first sub-module (Dimensionality Reduction) is responsible to produce an initial compact low-dimensional representation of a given high-dimensional data set. For instance, in our proposed PHySIS platform, CS will be exploited to carry out this step, in contrast to the DWT-based solution described in [RD 03], or the JPEG2000 compressor employed by Sentinel-2. Regarding the second sub-module (Encoding), this should be adapted to the inherent characteristics of the produced low-dimensional representation. For example, in [RD 03], a Bit-Plane Encoder (BPE) is utilized to encode the wavelet coefficients. In the PHySIS platform, the optimal encoding scheme, which best adapts to the characteristics of the generated CS random projections, will be a separate research topic. Thus, in the following, we will overview the general data formatting and packetization guidelines in order to be compatible with the CCSDS standard.

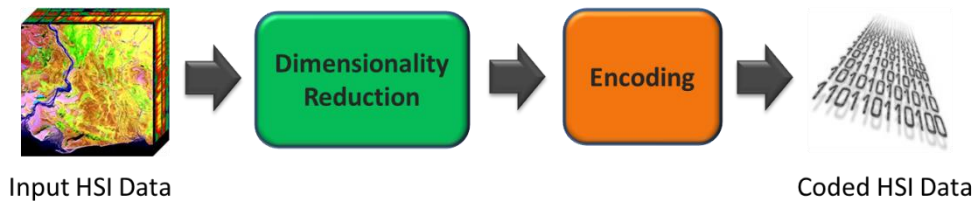


Figure 9: HSI data compression module

Table 13: HSI data compression parameters

	Compression method		**Input format**	
	Lossless	Lossy	Frame	Stripmap
PHySIS platform	✓	✓	✓	✓

3.3.3. Performance metrics

For a compressed image (hypercube), the bit rate achieved by the compression module, measured in bits/pixel (bits/voxel), is defined as the number of bits used in the compressed representation of the image (hypercube) divided by the number of pixels (voxels) in the image (hypercube). In case of lossy compression, several distortion or quality metrics have been introduced to quantify the degree to which the reconstructed image (hypercube) matches the original. Commonly used distortion or quality metrics are the following:

- ✓ Mean Squared Error (MSE) [distortion metric]
- ✓ Peak Signal to Noise Ratio (PSNR) [quality metric]
- ✓ Maximum Absolute Error (MAE) [distortion metric]

Furthermore, for a given compression module with a fixed set of parameters, the term *rate-distortion performance* or *compression effectiveness* is used to refer to the image (hypercube) quality achieved as a function of the bit rate. In the case of lossless compression, compression effectiveness is simply measured by the bit rate achieved. Notice also that compression effectiveness does not take into account any measure of implementation complexity (e.g., speed and memory requirements).

3.3.4. Data delivery

The encoded bit stream corresponding to an image frame or a stripmap consists of a single segment or a sequence of adjacent segments. Each segment contains a header followed by a coded data field. Depending on the operational mode selected, a segment can be of either fixed length or varying length. Moreover, the effects of a single bit error can propagate to corrupt reconstructed data to the end of the affected segment. This necessitates specific actions to be taken in order to minimize the number of potential bit errors on the transmission link. The transmission mechanism for the delivery of the encoded bit stream shall support, in the event of a bit error, the ability to relocate the header of the next segment.

If the encoded bit stream is to be transmitted over a CCSDS space link, several protocols provide specifications for transmitting the sequence of segments [RD 06] [RD 07] [RD 08]. Although in the PHySIS spaceborne application scenario we will rely on those high-level specifications, however, we emphasize that our goal is not to compete existing state-of-the-art space link implementations by designing a novel satellite data transmission mechanism.

Concerning a more precise structure (i.e., parts, sub-parts) of a segment's header, this will be possible upon determining the exact algorithmic details of our proposed CS-based HYP data compression method, along with the encoding scheme. For the moment, a generic structure of such a header will follow the specifications suggested in [RD 04], in terms of the recommended parts and their corresponding size (in bytes), as shown in Figure 10 and Figure 14. Data delivery will be also related to the *quantization* method to be developed for quantizing the low-dimensional representation prior to its encoding. Specific parameter values for this operation will be set having studied the properties of a suitable quantizer for CS random projections generated from HYP data.

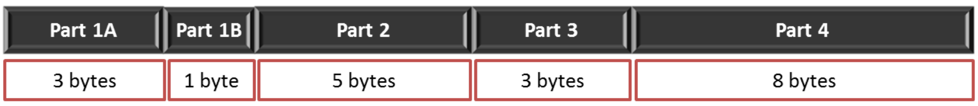


Figure 10: Generic structure of a segment header

Table 14: Overview of segment header functionality

Header part	Size (bytes)	Status	Content
Part 1A	3	Mandatory	• Flags for first and last segments of image or hypercube; • Indicates which of the optional header parts are included; • Encodes information that typically changes from segment-to-segment.
Part 1B	1	Mandatory (for the last segment of image or hypercube, not included otherwise)	Specifies issues related to the frame or hypercube formation (e.g., number of "padding" rows and/or columns to be deleted after image or hyper-cube reconstruction).

Part 2	5	Optional	Specifies limits on compressed bytes per segment, and limits on the fidelity with which low-dimensional representation will be encoded. This part can be included at the start of an image (hypercube) or application session, or at the beginning of each coded segment for variable output rate control.
Part 3	3	Optional	Coding options (e.g., number of blocks per segment). This information is typically fixed for each image (or hypercube) or application session, and can be included at the beginning of each image (or hypercube), but not in each segment.
Part 4	8	Optional	Image (hypercube) and compression parameters that must be fixed for an entire image (hypercube).

3.3.5. Data security

Traditionally, security mechanisms have not been employed extensively on civilian space missions. However, there has been an increasing trend towards the integration of security services and mechanisms. Although ground network infrastructures typically employ controlled or protected networks, however, in most of the cases, telecommands, telemetry, and science payload data, are still transmitted over unencrypted and unauthenticated Radio Frequency (RF) channels. As the operational environment becomes more hostile, this concept of operation becomes much more susceptible to attacks.

Undetected data modification or corruption is a major concern. It could affect the integrity (correctness) of data received either on the ground from a spacecraft or on the spacecraft from a ground station (i.e., what was received is exactly what was transmitted or any unauthorized modifications are detected and flagged). Modified or corrupted commands transmitted to the spacecraft could hinder its proper operation, whilst modified or corrupted payload data transmitted from the spacecraft could yield wrong scientific outcomes.

Depending on the considered application scenario, guaranteeing security of the acquired and transmitted data can be a critical issue. More specifically, security concerns the following aspects:

1. Data privacy
2. Data integrity
3. Authentication of communicating entities
4. Control of access to resources
5. Availability of resources
6. Auditing of resource usage

Concerning aspects 1)-3), these should be assured by the system and network operator on which the HSI platform is implemented and utilized. With respect to 4), it is assumed that access control to resources will be managed by the system, on which the compressor (encoder) and decompression (decoding) modules reside, noting that in a spaceborne application scenario these modules will be physically located separately from each other. In case of 5), we assume that adequate resources are available on both the encoder and decoder side. Finally, to address 6) we assume that auditing of resource usage will be handled by the management of systems and networks on which our HSI platform will operate.

Potential consequences of not applying security measures on our proposed HSI platform include potential loss, corruption, and piracy of the acquired data. The algorithms for information (e.g., data, image, video) confidentiality and authentication can be employed on any of the mission communications links, such as the forward space link (e.g., telecommand), the backward space link (e.g., telemetry, science data), as well as across the ground control stations network. Furthermore, they could be used to ensure confidentiality and authenticity of already stored data. Confidentiality is typically implemented by the use of encryption, whereas authentication is implemented by appropriate message authentication codes or via suitable digital signatures.

Confidentiality is defined as the *assurance that information is not disclosed to unauthorized entities or processes*. In other words, those who are not authorized are prevented from obtaining access to the protected data. For communications systems, there are two mechanisms for accomplishing confidentiality: (1) transmission through a physically protected medium; and (2) cryptography. For the CCSDS community, confidentiality must be implemented by cryptography for protection of information between end points that may be located on the ground and in space.

However, CCSDS does not impel at which layer the encryption algorithm will be executed. As such, there are multiple locations within the space communications layering model, where encryption can take place. Depending on the system, encryption might be implemented within the Application Layer, Network Layer, Data Link Layer, or even at the Physical Layer [RD 09].

On the other hand, authentication is the act of confirming the truth of an attribute of a single piece of data or entity. Authentication allows a receiver to establish, with confidence, the identity of the sender. Similarly, a receiver is also confident of data integrity, that is, that the data has not undergone unauthorized modification or alteration in transit without being discovered.

A commonly used authentication method is based on the notion of symmetric algorithms, where all communicating entities possess a shared “key” which enables them to encrypt, decrypt, and authenticate information shared among them. The way in which the shared key is distributed and managed among the users is decided by the end user.

For environments using symmetric keys, two types of algorithms are used to provide authentication and integrity of the data, namely, hash-based and cipher-based algorithms. Cipher-based techniques can better exploit the available resources when both authentication and confidentiality are required, since a single algorithm can be used for both. Furthermore, cipher-based methods can be more easily implemented in hardware than their hash-based counterparts.

For environments where public-private key cryptography is available, authentication and integrity can be accomplished using a digital signature algorithm. More specifically, the signer (origin) performs a hash over the data to be signed using a hash algorithm (e.g., Secure Hash Algorithm (SHA)). The resultant hash word is then encrypted using the signer's private key to create the digital signature. On the receiver side, the signature of the received signed data is verified to assure that the data came from the claimed entity and has not been modified. To authenticate the signature, the message digest is decrypted using the signer's public key, which can be sent with the data, cached by the receiver if previously obtained, or it can be obtained from a public key server if it has been posted.

In order to achieve a minimum baseline all CCSDS missions use the Advanced Encryption Standard (AES) algorithm [RD 10]. CCSDS implementations typically use a 128-bit key, however, AES supports larger key sizes (192-bits, or 256-bits) for stronger security. If, on the other hand, encryption in combination with data integrity and origin authentication is required, implementations typically employ Galois/Counter Mode (GCM) [RD 20] [RD 21].

We emphasize though that the implementation of a high-end security module is out of the scope of PHySIS. Instead, we will study the inherent capability of our proposed CS-based algorithms in providing a minimum level of encryption of the acquired HYP data.

3.4. Recovery of HSI data from IMEC's *m*osaic architecture

One of the key signal processing techniques that we will consider in image demosaicing. In general, to acquire a colour image, modern cameras employ a colour filter arrays (CFA) in order to map each pixel into a single colour, before the image is acquired by the sensor. As a result, the captured intensities values depend on the CFA that was applied on every image location. However, in the recovery process of the original RGB image, the existence of multiple missing colour components is intense. The reconstruction of the RGB image from the single-color-per-pixel CFA image is widely recognized as the demosaicing problem.

Over the last decades multiple algorithms were constructed to approach this problem, including edge-directed interpolation [RD 28], frequency-domain edge estimation [RD

29], dictionary learning [RD 30], etc. The following section provides some state-of-the-art innovative sparse-based techniques.

State-of-the-art demosaicing approaches rely on the sparse representation of pixels and blocks of pixels on appropriately designed dictionaries. The authors in [RD 27] propose a dictionary learning based colour demosaicing technique, for the recovery of a full-colour light field from a captured Plenoptic image. The authors use a Lytro Plenoptic camera in order to capture and process light fields. Generally, light field cameras typically capture colours placing a Colour Filter Array (CFA) on the sensor. The Lytro camera utilizes a Bayer type CFA that forces each pixel to capture only one colour component (Red, Green, and Blue). However, the Bayer filter introduces gaps in the full colour light field. For this purpose, a proper demosaicing algorithm is critical to recovery the missing colour information.

While traditional demosaicing methods consider only spatial correlations between neighbouring pixels on a captured Plenoptic image, their method takes advantage of both spatial and angular correlations in naturally occurring light fields, utilizing the basic theory of dictionary learning and sparse optimization.

Specifically, at the training step, the authors learn a compact dictionary, from all the spatial, angular and colour correlations of rays in a light field from a set of training images captured by a Lytro camera. The resulting dictionary is directly used to synthesize an estimate of a full-colour light field, from the captured Bayer-filtered light field. The key component of this work is the extraction of the proper sparse coefficient vectors, that provide a suitable representation of the light filed in a dictionary basis.

Another sparse-based demosaicing approach is proposed in [RD 31], where the authors provide a comparison between the Bayer and the random panchromatic colour filter array (CFA) structures under the sparsity optimization framework. They demonstrate that a random panchromatic CFA under certain incoherence constraints outperforms the Bayer based sparse recovery. Additionally, in [RD 30] the authors provide a novel method of demosaicing and super-resolution for a colour filter array, combining the residual image reconstruction with the sparse representation framework. Their algorithm considers as input an intermediate image that was generated by demosaicing and super-resolution, and reconstructs the residual image utilizing the sparsity measure as a proxy. A dictionary matrix is learned from a large set of measurements composed of both intermediate and residual images.

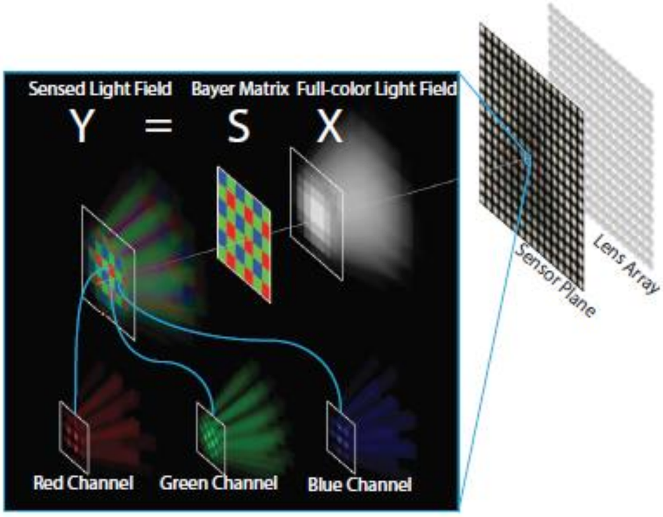


Figure 11: Bayer Filter utilized in a Plenoptic camera

The application of compressed sensing (CS) and sparse representation (SR) frameworks can be instrumental in the multispectral and the hyperspectral image demosaicing problem. Figure 12 presents a schematic illustration of the considered HSI data acquisition and recovery based on the IMEC mosaic architecture. In the IMEC mosaic architecture, each acquired frame is composed of pixels where each pixel is associated with a different spectral band. Decomposing this frame into its constituents reveals that for each spectral band only a small number of spatial location are sampled. The objectives in mosaicing is to estimate the remaining measurements that will complete each spectral frame and provide the full resolution hypercube.

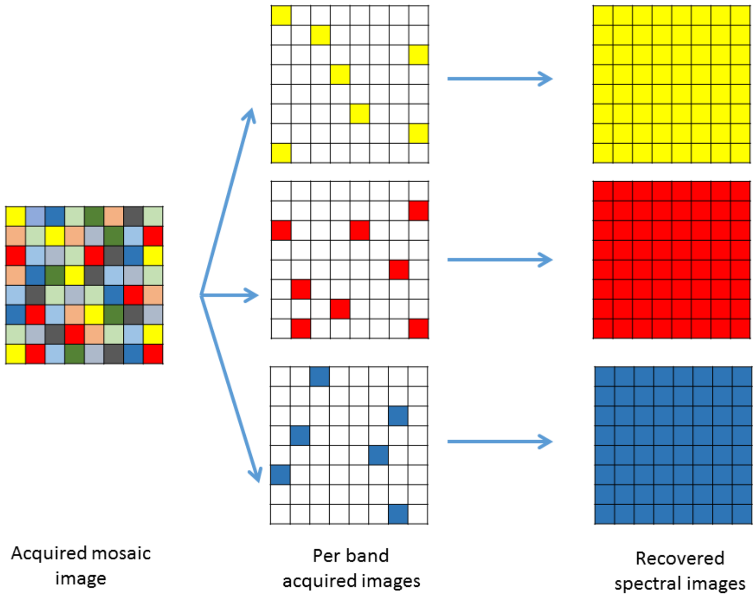


Figure 12: Demosaicing for IMEC mosaic HSI imager data

3.5. PHySIS HYP data enhancement and restoration

The software development tasks, which are related to image restoration issues, aims at developing recovery algorithms to tackle inverse problems in hyperspectral imaging. In the PHySIS project we will mainly focus on three key inverse problems in imaging science: denoising, deconvolution and compressed sensing recovery (i.e. decompression for compressed measurements). The expected gains and specifications of the proposed software will be based on two major criteria: restoration efficiency and computational cost.

Restoration efficiency will be based on the mean square error (MSE), which is a standard measure of quality in imaging science. Software evaluation will carried out on simulated data. Since the proposed methods will be built on high-end non-linear processing algorithms, efficiency forecasting is a challenging task. More precisely, the efficiency of the developed software will depend on the restoration task as well as the signal itself.

Fortunately, preliminary evaluations that have been investigated in the last few years provide a good indication on the expected recovery gains. It has been shown that implementing recovery software that can account for both the spatial and spectral sparsity of hyperspectral can lead to a MSE gain of 5-10 dB with respect to standard methods [RD 18]. Since these results have been derived from synthetic simulations, it might probably provide a gross upper bound on the expected gain one can reach on real hyperspectral images.

The evaluation of the recovery efficiency/compression rate performances in the context of compressive sampling will also highly rely on the specific data to be processed. At this point, one can merely conjecture some upper bound on the expected compression ratio. This is particularly challenging since the performances of CS-based HSI systems have seldom been studied in realistic situations, especially when more sophisticated acquisition conditions need to be accounted for (e.g. Poisson noise, outliers, calibration errors, etc.). A CS-based hyperspectral imaging prototype has been thoroughly studied in a biological application [RD 19]. This study suggests that compression ratios of about 10 can be expected from a CS-based HSI system without significant loss of recovery performances. One can however expect that the hyperspectral data to be analysed in the PHySIS project will benefit from a lower noise contamination, which suggests that better compression ratios might be reached without significant alteration of the recovery quality.

Hyperspectral image recovery algorithms based on sparsity make profit of the latest advances in operational research, which however implies a non-negligible computational cost. For typical hyperspectral images, which are composed of a few million pixels, the processing time of the proposed restoration algorithms is of the order of a few minutes to a few hours on a standard personal workstation, with a memory requirement of the order of 5-10 times the space needed for data storage. If processing times is a limiting issue or large-scale hyperspectral data need to be processed during the project, parallelized versions of the proposed algorithms can be envisaged so that data processing can be performed on a high-performance computing facility. For that purpose, it is important to notice that a multi-core cluster is available at CEA.

3.6. PHySIS HYP data understanding

Hyperspectral image understanding refers to the process of extracting useful spectral information from the collected hyperspectral data (Figure 1). In PHySIS, we focus on two problems of hyperspectral image understanding, namely *hyperspectral unmixing* and *hyperspectral clustering*.

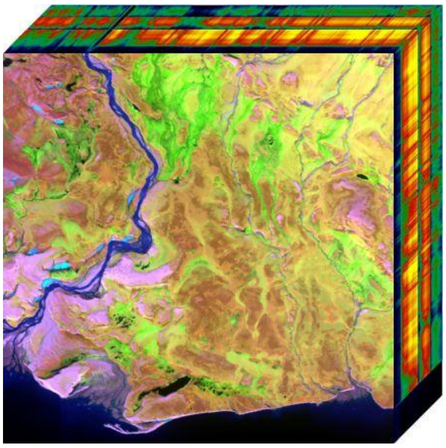


Figure 13: Hyperspectral image cube

Hyperspectral unmixing (HU) is a prominent task in hyperspectral image processing. For low spatial resolution hyperspectral images, more than one materials may be mixed in each image pixel. HU aims at identifying materials present in a captured scene, as well as estimating their proportionate abundances in each pixel. Figure 14 depicts four abundance maps, which are estimated using a HU method for a subset of the well-known AVIRIS "cuprite" data cube having size 250 rows by 191 columns by 188 bands. It is observed that each material has a prominent presence in only a few of the scene pixels.

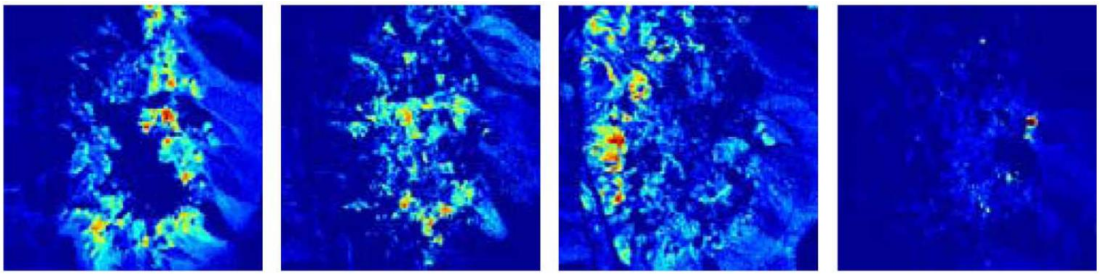


Figure 14: Estimated abundance values of four endmembers in the cuprite dataset.

In high spatial resolution hyperspectral images, clustering aims at assigning pixels of the same material to the same group (cluster) and pixels of different materials to different clusters. Clustering applied to hyperspectral images is a very interesting and challenging problem, due to, a) the high dimensionality of hyperspectral data, b) the noise, affecting in different ways different spectral bands and c) the high spectral redundancy that leads hyperspectral image pixels to form not easily distinguishable clusters. Figure 15 depicts one spectral band of a hyperspectral image acquired by HYDICE over Washington DC Mall that includes the Lincoln Memorial and the result of clustering the pixels of the image. The size of the image is 150 rows by 150 columns by 191 bands. It is observed that each pixel is assigned to a unique cluster/material.

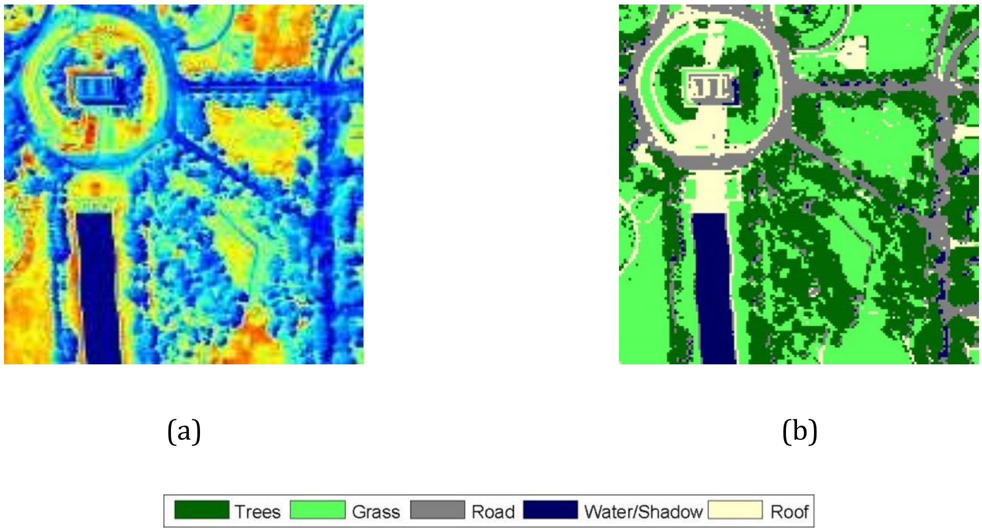


Figure 15: (a) The Washington DC Mall data set at a specific spectral band and (b) a clustering result. The correspondence between the clusters and colors is given below.

3.6.1. Requirements for PHySIS

In the framework of the PHySIS project, we shall consider two sources of earth observation hyperspectral data, namely, Sentinel-2 and PRISMA imagery data. Let us highlight here some of these hyperspectral sensors' special characteristics that have a prominent role in performing spectral unmixing and clustering. In the Sentinel-2 mission, the MultiSpectral Imager (MSI) instrument features 13 spectral bands spanning from the VNIR (Visible and Near Infrared) to the SWIR (Short-Wave Infrared) in the range of 400 nm – 2400 nm with a swath width of 290 km. Specifically, MSI features 4 spectral bands at 10 m, 6 bands at 20 m and 3 bands at 60 m spatial resolutions, while its spectral resolution is 15 nm – 180 nm. The expected maximum data amount per day is 1638.4 GB. PRISMA is an Agenzia Spaziale Italiana's mission based on a hyperspectral/panchromatic (HYP/PAN) payload with spatial resolutions of 30 m and 5m respectively, a swath width of 30 km, a spectral range of 400 nm - 2500 nm (HYP, i.e. VNIR and SWIR) and of 400 nm – 700 nm in PAN. The expected maximum data amount per day is 43GB.

At a ground station processing level, it is envisaged that data acquired from both Sentinel-2 and PRISMA satellites, related to the same area of interest on the ground, will be fused and jointly processed to provide better unmixing and classification results. To this end, it is the characteristic attributes of the captured hyperspectral imagery data, such as the spectral and spatial resolution, that will determine the preferable unmixing and clustering technique to be applied to the data. Different techniques can be applied and their results can be combined and compared, so that hyperspectral image understanding is enhanced. Moreover, in a joint unmixing/clustering scheme, the results obtained by unmixing algorithms, i.e., estimated abundance maps for each material present in the image, can serve as input to a clustering method. In this way, it is anticipated that the synergy between unmixing and clustering will improve clustering performance and disentangle valuable information from hyperspectral imagery data.

A task of major importance towards hyperspectral image understanding is also ground truth validation. Ground truth refers to a process by which a pixel on a hyperspectral image is compared to what is there in reality (at the present time) in order to verify the contents of the pixel on the image. Ground-truth sampling aims at providing information on the geophysical properties, especially in cases, where the region understudy is a land cover. However, this is often difficult to perform in practice. To this end, ground-truth validation may be achieved by considering other relevant studies that concern the same land region as a reference for comparing results.

The applications of both Sentinel-2 and PRISMA missions include environmental monitoring, land cover and agricultural landscapes mapping, as well as monitoring the quality of inland waters and the Mediterranean Sea. It is the nature of these applications that implicitly suggests that there is no critical time constraint on the provision of data products. Hence, hyperspectral imagery data can be stored at the ground station and later on processed by spectral unmixing and classification algorithms in an offline mode. Although offline algorithms need more computation time than online algorithms do, they, in principle, provide more accurate results. Actually, the majority of hyperspectral image processing algorithms reported in the literature belong to the family of offline processing algorithms.

Offline processing algorithms require a bunch set of data to be available a priori. However, as the amount of available imagery data grows, system performance requirements are increasing dramatically. This data deluge necessitates the development of parallel and distributed computing systems that support different types of parallelism. Moreover, hyperspectral image processing is known to be a computationally intensive task that requires large amounts of computation power. Within the PHySIS project it is envisaged that computationally efficient unmixing and clustering algorithms will be developed. A recent development in hyperspectral image analysis algorithms is their implementation in graphics processing units (GPUs). GPUs have recently emerged as a promising parallel architecture considering the rapid growth of its computational power in comparison with uniprocessors. The main prerequisite for the implementation of spectral unmixing and classification algorithms in GPUs is their formulation based on vector-by-vector operations, i.e., inner products. This is a requirement that can be easily met considering the variational or adaptive nature of algorithms that have been recently proposed by the NOA team.

4. Discussion

The application scenarios presented in the previous sections dictate the key constraints and specifications which guide the PHySIS system requirements. The scenario descriptions addressed application needs, operational constraints, technical issues, allowing for the identification of the design parameters that play a critical role in the overall performance of the system as a whole.

The hardware specifications presented in the report will be investigated under the prism of CS-enabled imaging architectures in order to provide disciplined solution to the limitations of state-of-the-art methods. In all cases, we will consider the HSI camera systems developed by IMEC with an emphasis on the IMEC mosaic pattern design.

The second version of this deliverable, *"D2.3: Scenario descriptions and system specification (v2),"* which is due on M12, will provide an updated and detailed description of the system based on the initial results and achievements obtained during Year 1 of the PHySIS project.