Focus on PRISMA Hyperspectral Image Simulator: functionalities and applications

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ABSTRACT

PRISMA (PRecursore IperSpettrale della Missione Applicativa) is an Italian hyperspectral mission, scheduled for launch in 2018. It is an Earth Observation project fully founded by the Italian Space Agency (ASI; Agenzia Spaziale Italiana). The PRISMA Mission aims at qualifying the technology, developing applications and providing products to institutional and scientific users for environmental observation and risk management. Several fields may benefit from the scientific use of the PRISMA product: agriculture and forest, geology, urban areas and water resources. The PRISMA satellite will be placed on a sun-synchronous orbit at 620 Km nominal altitude, embarking a state-of-the-art hyperspectral and panchromatic payload able to acquire areas with a 30 km swath width. The hyperspectral sensor, with a Ground Sampling Distance (GSD) of 30 m, will cover the wavelength range from 400 nm to 2500 nm with 10 nm spectral sampling through two partially overlapped spectrometers. The panchromatic camera instead will acquire the same area with a spatial resolution of 5 m GSD. A Hyperspectral Image Simulator (HSIS) has been included in the PRISMA system. The main objective of HSIS is to allow the verification of the production chain before its integration in the Processing Subsystem, thanks to its capability of simulating all the relevant knowledge about the instrument, the orbit, the radiation source, the atmosphere and the observed scene. The Image Simulator takes in input either synthetic or real surface reflectance/radiance images compatible with PRISMA sensor characteristics and atmospheric, instrument and platform parameters to define the simulation scenario. The Instrument simulator implements in a modular and fully parametrized architecture all the functions relevant to the full path of conversion of the impinging photon flux to the Digital Numbers produced at instrument electronics output (L0 data). The modules comprise image projection and propagation through telescope to HYP (hyperspectral) and PAN (panchromatic) focal planes, with spatial optical effects (distortion, aberrations, smile/keystone, motion effect, etc.), spectral filtering (channels dispersion, SRFs) and full detection chain effects (background and dark signal, noise, non-uniformities, etc.). As output the HYP and PAN PRISMA L0 Products are generated and formatted in the CCSDS (Consultative Committee for Space Data Systems) format.

INTRODUCTION

PRISMA (PRecursore IperSpettrale della Missione Applicativa) is an Italian Earth Observation (EO) mission, commissioned and funded by the Italian Space Agency (ASI, Agenzia Spaziale Italiana) with the aim of providing the EO community with a state of the art system capable to deliver hyperspectral data acquired with a worldwide coverage.

The PRISMA programme is currently in the development phase, approaching the System Critical Design Review (CDR) and the launch is scheduled in 2018. The system is composed of a Ground Segment and a Space Segment, the latter consisting in a single small class spacecraft, with a mass of about 830 kg, placed on a frozen sun-synchronous orbit with a repeat cycle of 29 days (430 orbits) [1]. The orbit mean altitude is about 614,8 km with an inclination of 97.851° and the Local Time of Descending Node is 10.30 AM. In order to guarantee a worldwide coverage, the primary area of interest for the PRISMA mission has been defined in the following latitude and longitude ranges: Longitude: 180°W - 180°E, Latitude: 70°S - 70°N.

The PRISMA Payload [2] consists of an Imaging Spectrometer, able to acquire in a continuum of spectral bands ranging from 400 to 2500 nm, and a medium resolution Panchromatic Camera (PAN). The two sensors (hyperspectral and panchromatic) have been combined in the same payload to perform observations based on recognizing the geometric characteristics of the scene and, at the same time, determine the chemical-physical characteristics of the targets of interest in the observed scene.

The main Payload subsystems are the following:

- Hyperspectral/PAN Optical Head, that collects the incoming radiation through a telescope and disperse it through two spectrometers that convert photons to electrons by means of appropriate detectors, amplify the electrical signal and convert it into digital counts.
- Main Electronics (ME), based on a redundant sub-assembly architecture, is devoted to the control of the instrument and to handle the bit stream representing the spectral images up to the interface with the spacecraft transmitter.
- Sun Protection System, an autonomous system, directly connected to the payload ME and independent from the spacecraft, that is meant to activate a recovery reaction in case of failure of Attitude and Orbit Control System so to prevent direct sun flux entering inside payload main optical channel.

The PRISMA Hyperspectral sensor utilizes the prism to obtain the dispersion of incoming radiation on a 2-D matrix detectors in order to acquire several spectral bands of the same ground strip. The “instantaneous” spectral and spatial dimensions (across track) of the spectral cube are given directly by the 2-D detectors, while the “temporal” dimension (along track) is given by the satellite motion (pushbroom scanning concept). The following table summarizes the key Payload technical features.

Table 1: Payload technical features

Swath / FOV	30 km / 2.77°
GSD	Hyperspectral: 30 m PAN: 5 m
Spatial Pixels	Hyperspectral: 1000 PAN: 6000
Pixel Size	Hyperspectral: 30×30 μm PAN: 6.5×6.5 μm
Spectral Range	VNIR: 400 – 1010 nm SWIR: 920 – 2500 nm PAN: 400 – 700 nm
Spectral Sampling Interval (SSI)	≤ 12 nm
Spectral Width	≤ 12 nm

Once the data have been acquired and downlinked to the station, the PRISMA ground segment will be able to daily generate and distribute to the users up to 200 products sized 30×30km, with different processing levels according to the requests. The levels of processing are the following:

- L0 Product: it includes decompressed hyperspectral and PAN bands, containing the information about the Cloud Coverage percentage.
- L1 Product: it is a Top-of-Atmosphere (ToA) radiance file, stored in a Hierarchical Data Format (HDF5).
- L2 Product: three different products belong to this category:
    - atmospheric corrected and geolocated product (L2b)
    - at-surface spectral reflectance map, including aerosol optical thickness and water vapour map (L2c)
    - geocoded surface reflectance product (L2d), that can be georeferenced with or without ground control points (GCP) according to user request and availability.

In order to test and evaluate the performances of the L1 and L2 processors, it has been included in the PRISMA system a Hyperspectral Image Simulator (HSIS), that will be described in detail in the following sections.

HSIS FUNCTIONS

The hyper-spectral image simulator for PRISMA mission produces simulated PRISMA-like imagery in the spectral range of interest ([0.4-2.5] μm) integrating into a single tool all the relevant knowledge about the instrument, the radiation source, the atmosphere, and the observed scene and considering:

- orbital and attitude movements of the satellite during push-broom acquisition;
- Sun ephemerids and atmospheric effects;
- Earth surface properties as reflectivities and/or ToA radiances, Digital Elevation Models;
- Electro/Optical sensor characteristics taking into account geometric, spectral and radiometric behavior;
- Generation of the Digital Counts and L0 formatting in the CCSDS format.

HSIS performs the mapping from Earth surface to sensor detector array, taking into account the geometry of image acquisition (satellite position, orbit and attitude, digital elevation model of the acquisition scene). Then, the radiance at the top of the atmosphere is computed, from the surface reflectance data by applying the radiative transfer model including a Lambertian surface model. The radiative transfer model is implemented by using the Moderate Resolution Transmittance Code (MODTRAN) 5, while the effects of surface shading and of the shadow are modelled by considering a DEM as input and Sun effemerids at the acquisition time. At this stage, HSIS generates the hyperspectral and panchromatic radiances images at the Top of Atmosphere as perfect sensor images. In particular, the image formation on the moving focal plane is performed considering an ideal push-broom linear array generation along input pre-defined orbit and with the temporal law of the satellite attitude as defined by input parameters, without optical distortion and noises and carried by a platform without neither attitude nor orbit perturbations.

The successive simulation process is the application of all the realistic effects generated by the electro/optical system. To this aim, HSIS includes, in addition to service modules for multi-dimensional data manipulation, the following main modules:

- A spatial module to apply the spatial filtering effects to the acquired images, introduced by the instrument optics, the pushbroom scanning motion, the disturbances (drift, jitter), the pixel response.
- A spectral module to apply the spectral response functions of each band to the spectral irradiance impinging on instrument focal planes (VNIR, SWIR, PAN).
- A radiometric module, implementing the full electronics detection chain generating discretized pixel signals in output from the instrument on-board processing board, including pixel-by-pixel distributions of gain, offset, noise.

The output data in digital counts from VNIR-SWIR channels has 3D dimensions (samples, lines, bands), the PAN channel output has 2D dimensions (samples, lines). The raw data is formatted into CCSDS packets.

HSIS models and processing flow

The Image Simulator ingests as input either synthetic or real surface reflectance/radiance images compatible with PRISMA sensor characteristics. Input radiance and/or reflectance data can be generated starting from synthetic images or from other satellite or airborne hyperspectral radiance images. Such images needed to be i) orthorectified in order to be placed on the Earth surface reference system and ii) opportunely spatial/spectral re-sampled in order to make them compatible with the PRISMA system. If atmospheric modelling is required in the simulation, a reflectance hypercube is required as input to HSIS. A reflectance hypercube can be built synthetically by using a land cover map and a reflectance spectral library or by atmospherically correcting satellite or airborne hyperspectral radiance data.

The reconditioned surface reflectance/radiance images can be archived in the simulator repository to be further used as input in the simulation process.

Once Operator has set the atmospheric, instrument and platform parameters to define the simulation scenario and selected the input scenes, the simulation is run and as output the Digital Counts (DC) Products are generated. Such products are obtained adding to the input scene effects due to atmosphere, satellite platform movement and sensor effects.

The Image Simulator is structured as a series of modules, each of them having in input the necessary processing parameters/files and generating as outputs intermediate product files:

Geometry Unit: performs the mapping from Earth surface to sensor detector array, taking into account the geometry of image acquisition (satellite position, orbit and attitudes, lines of sights of the detector pixels and the digital elevation model of the acquisition scene). The perfect sensor array is dynamically generated by simulating the pushbroom image formation mechanism. At each instant, the pixels in the PAN linear array formed by 6000 pixels and in the HYP linear array, formed by 1000 pixels (assumed before the prisma diffraction) are projected on the ground surface characterized by a DEM. The radiances/reflectivities are extracted by interpolating the values in the intersection points. To this aim, the sinc interpolation is exploited in order to preserve the original frequency content of the scene. This process is repeated for each line acquisition time by modifying the position of the PAN and HYP linear arrays along the orbit and changing the line of sight depending on the input sensor attitude profile (default value are such that pitch and yaw have nominal values 0.0° and roll is equal to the wanted roll angle +-30°).

Atmosphere Unit: provides the radiance at the top of the atmosphere starting from the surface reflectance data, the ToA solar irradiance and the atmospheric profile setting. It is enabled only if input data are reflectance.

In the Visible to SWIR spectral regions the radiation collected by sensors depends mainly on radiation originated by the sun. The following most significant at–sensor radiation components can be distinguished (see Figure below):

- the un-scattered surface reflected radiation (red line),
- the down-scattered surface reflected skylight (green line),

- the up-scattered path radiance (blue line).

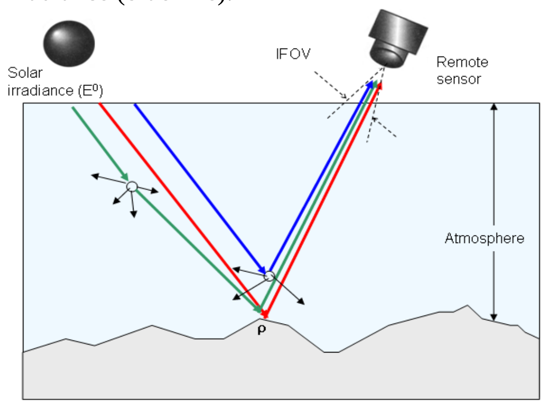


Figure 1 –Scheme of the radiative transfer model

The total at sensor spectral radiance L_λ^s is the sum of such three radiance components.

The radiative transfer model is applied to the input reflectance data by using the model MODTRAN 5. The modelling takes into account all most relevant atmosphere contributions as:

- spectral transmission, emission and scattering by the atmosphere which depend upon the atmospheric conditions (temperature), content (gas amounts, aerosol types and concentrations) and the path geometry;
- the surface diffusion, based on Lambertian model, including effects such as shading and shadows due to orography modelled by a DEM.

Some more advanced parameters can be introduced through the ingestion of maps in order to spatially characterize the atmosphere: vertical water vapour column, visibility and Angstrom Law offset to define the aerosol optical depth, the extinction coefficient for accurate cloud model.

Electro/Optical Sensor Unit: provides the model of the electro/optical system in order to retrieve VNIR, SWIR and PAN products as acquired by the PRISMA instrument. It takes into account the spatial, spectral and radiometric responses due to the push-broom image formation mechanism, the platform induced disturbances, the imaging optics, the spectrometer dispersing elements, the detectors and readout electronic chain.

The instrument simulator architecture is modular, and the variables representing hardware characteristics are implemented as configurable parameters. The modular architecture improves reusability of where needed, e.g. the PAN channel uses the same spatial and radiometric modules, with different input parameters, of the VNIR and SWIR channels. The modular approach is limited by the physical inter-dependencies between functions and effects, so it is has not been always possible to make a clear division in separate modules. In figures below, the classification of architectural modules is the following:

- Blue modules implement geometrics and optical functions
- Green modules implement spectral functions
- Red modules implement radiometric functions
- Gray modules implement software functions (parsing, checking, data formatting)

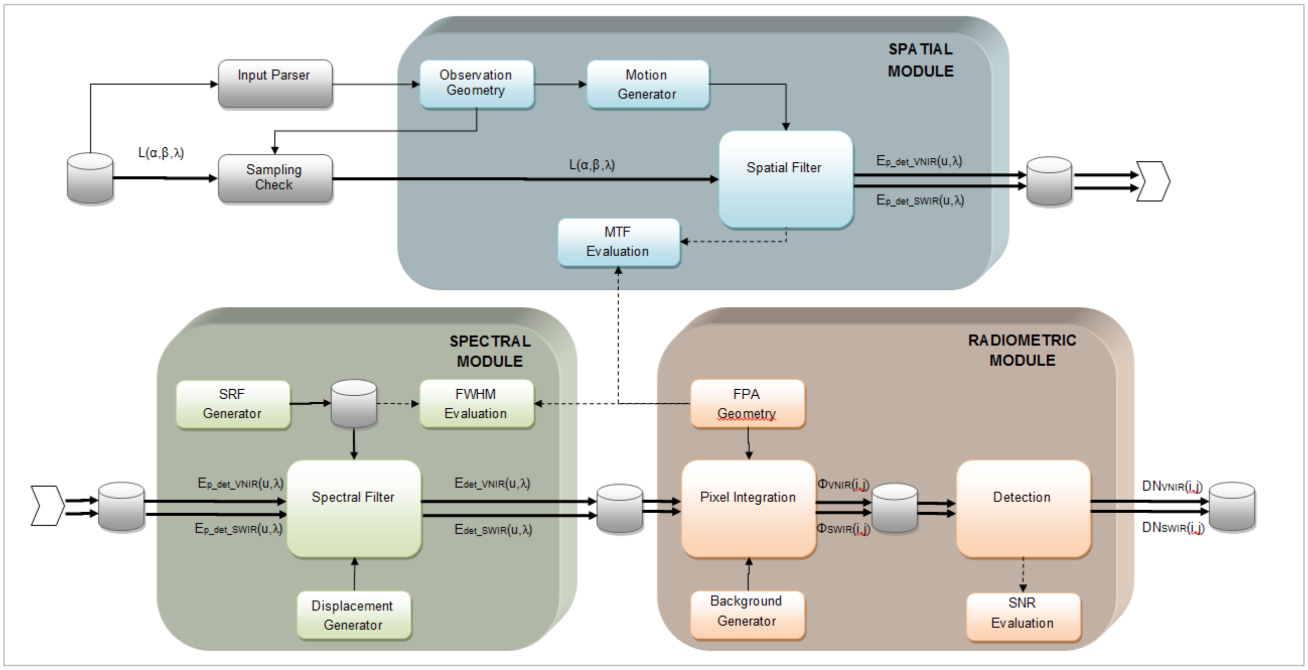


Figure 2 – VNIR/SWIR channels: simulator architectures

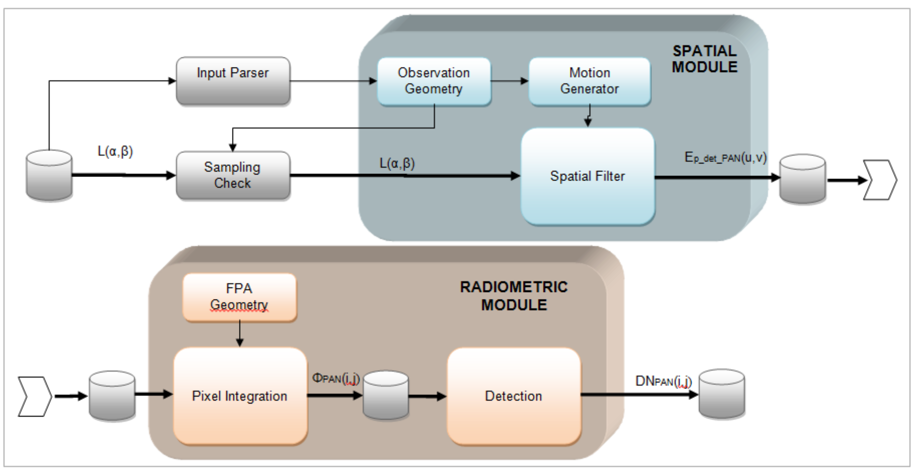


Figure 3 – PAN channel: simulator architecture

Spatial module generates and applies, for each wavelength of the input spectral radiance cube, the instrument fore-optics point spread function (PSF), including diffraction and aberrations for different field zones, the motion effects (scanning, jitter, etc.), the spectrometer optics PSF. Telescope field curvature and Smile effects are applied in this module.

Spectral module generates and applies the full set of spectral response functions (SRFs), starting from the spectrometer optics and dispersing characteristics. Keystone effect is applied in this module. Alignment position of detector pixels w.r.t. filtered spectral irradiance impinging on the focal plane are taken into account.

Radiometric module applies for each pixel all the transformations from impinging photon flux at different wavelengths to digital counts, considering the responsivity, temporal noise (shot, dark, readout etc.), electronics offset, amplification and digital conversion. Thermal background of the spectrometer elements in view of the IR detectors causes an additional thermal signal which is accounted for in this module. Defective pixels too are configured and simulated within this module.

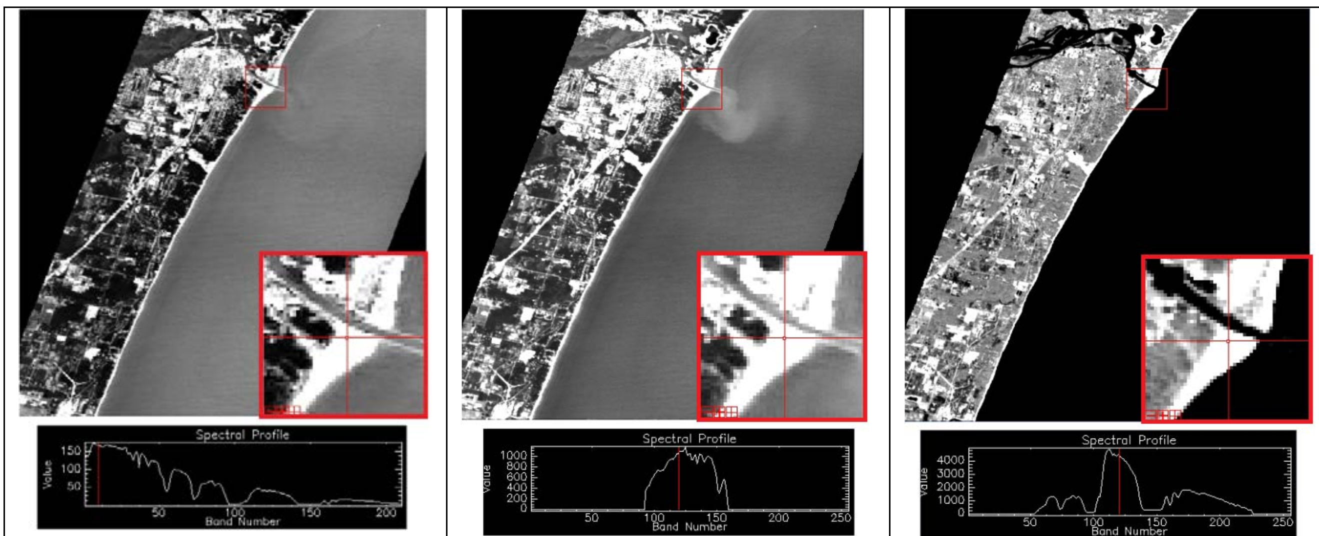
An additional L0 adapter module works on the output digital data from the VNIR-SWIR and PAN channels, formatting the raw digital counts into CCSDS packets.
The Geometry Unit and the Atmosphere Unit above described are performed for each pixel of the input HYP data, taking into consideration that for each pixel all the wavelengths have the same line of sight as expected before the prisma diffraction, and for each pixel of the input PAN image. As output, the HYP and PAN Radiances at the ToA, as acquired by an ideal pushbroom linear array, without electro/optical distortion and noises and carried by a platform without neither attitude nor orbit perturbations, are generated and archived.

Then, HYP and PAN Perfect Sensor ToA Radiances are the input of Electro/Optical Sensor Unit that generates the complete payload radiometric, spectral and geometric HYP and PAN data as acquired by the PRISMA Electro/Optical payloads.

Instrument performance have to be assessed by generating input scenarios compatible with mission requirements and retrieving the available intermediate outputs from the simulator modules to check mainly for: MTF, SNR, SRF FWHM (spectral resolution). Finally, end-to-end functional analysis have been performed to test the complete simulation chain through all implemented functions.

HSIS product example

In the following, an example of simulated images based on radiances retrieved from AVIRIS Hyperspectral data (data code: f080709t01p00r13rdn). The ingested radiances are acquisition over the coast Michigan lake south of Manistee National Forest (Grand and Kalamazoo River Outlets, MI) in 2008, 8th July.



a) Hypercube of the ToA Radiances before the application of the HYP sensor model	b) VNIR channels Digital Counts	c) SWIR channels Digital Counts (SWIR channel has a 2 different gains in the wavelengths ranges 995nm-1400nm, and 1400nm-2500nm)

Figure 4 – VNIR and SWIR DC results: scene on top left image, detail on the red square and spectral profile for the central point of the detail in the bottom plot.

Case study with HSIS

HSIS can be used at several stages to support validation and capability of products for supporting applications. Three cases are considered depending on the product level to validate: Level 1, Level 2 and Level 3/4 cases.

Case #1: Level 1 validation

HSIS provides a TOA radiance hyperspectral cube to feed the sensor model and generate DN data formatted as science packet. Therefore a comparison of input TOA radiance and L1 Product TOA radiance as a function of sun irradiance, surface albedo and compression ratio can be performed. Instrument performance can be assessed by generating input scenarios compatible with mission requirements and retrieving the available intermediate outputs from the simulator modules to check mainly for: MTF, SNR, SRF FWHM (spectral resolution).

Case #2: Level 2 validation

Surface reflectance generation depends upon many factors that are difficult to control without support of ground truth and atmospherical data acquired with specific campaigns. To this aim, a support can be provided by HSIS using synthetic test scene, containing patchworks of known species under different irradiation and atmospheric conditions, in order to assess the capability of the L2 processor to reconstruct the surface reflectance.

Case #3: Level3/4 support to validation

The use of synthetic scene of pure species can be extended by generating patchworks of mixed species to support a sensitivity analysis of the species retrieval capability at sub pixel level.

CONCLUSIONS

This paper provides a detailed description of the PRISMA image simulator HSIS, that has been designed and developed in the framework of the PRISMA programme with the aim of testing and evaluating the performances of the L1 and L2 processors. Moreover, the processing workflow has been illustrated and an example of HSIS results has been provided, based on AVIRIS Hyperspectral input data.

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