# The EnMAP Hyperspectral Satellite Mission An Overview and Selected Concepts

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***Abstract*— The German Aerospace Center DLR – namely the Earth Observation Center EOC and the German Space Operations Center GSOC – is responsible for the establishment of the ground segment of the future German hyperspectral satellite mission EnMAP (Environmental Mapping and Analysis Program). The Applied Remote Sensing Cluster has long lasting experiences with air- and spaceborne acquisition, processing, and analysis of hyperspectral image data. This paper mainly addresses the concept of the operational and automatic processing chain and the calibration / data quality to generate high quality data products.**

***Keywords:***

## I. INTRODUCTION

EnMAP (Environmental Mapping and Analysis Program; www.enmap.org) is the first German spaceborne hyperspectral Earth observing mission [12]. The launch is scheduled for 2015 with a following five years of mission operations. EnMAP will provide information about the status of different ecosystems and their response to natural or man-made changes of the environment. The major components of the EnMAP project are the project management by the Space Agency of the German Aerospace Centre (DLR), the space segment headed by Kayser Threde GmbH, which is responsible for the hyperspectral instrument [16] and the satellite bus (established by OHB-Systems Bremen, Germany, in contract), the science advisory group headed by GFZ and finally the ground segment realized by DLR. In the first part an overview of the mission is given composed of the space and the ground segment. In the second part the generation of the standardized products is described, which will be delivered to the international user community of science and industry coordinated by GeoForschungsZentrum Potsdam GFZ as the mission principal investigator [4]. Especially the geometric simulation, characterization and processing is described and how to achieve highly accurate and co-registered products. In the following parts an overview of the radiometric in-flight calibration concept is given (e.g. dark value measurements, deep space measurements, internal lamps measurements, Sun measurements). During the mission lifetime, the spectral and radiometric behavior of the sensor varies within narrow limits. Therefore, in-flight calibration is necessary to ensure a spectral accuracy of better than 0.5 nm and radiometric accuracy of better than 5%. Complemented by pre-launch calibration and characterization these analyses will deliver a detailed and quantitative assessment of possible changes of spectral and radiometric characteristics of the HSI.

## II. ENMAP MISSION OVERVIEW

The space segment consists of the satellite bus and the hypesrpectral instruments (Figure 1). To measure frequently quantitative parameters which describe key processes on the earth's surface, the EnMAP satellite will be able to revisit any location on the earth globe under a quasi-nadir observation (max. across track off-nadir pointing angle +/- 5°) each 21 days under defined illumination conditions (sun-synchronous orbit at 653 km altitude with an 11:00 o'clock LTDN crossing). Utilizing the off-nadir across pointing capability of +/-30° the target revisit time will be within 4 days. Besides the AOCS payload consisting of three star sensors, gyros and GPS the satellite bus will contain two imaging spectrometers (VNIR: Visual and Near InfraRed and SWIR: Short Wave InfraRed) operated in pushbroom configuration. During the five years of mission operations in the years from 2015-2020 data will be acquired with a spatial ground sampling of approximately 30 m × 30 m at nadir and a swath width of 30 km. The HyperSpectral Instrument (HSI) will be designed and realized as a 2-dimensional CMOS (Complementary Metal Oxide Semiconductor) focal plane array for the VNIR spectral region and a 2-dimensional MCT (Mercury Cadmium Telluride) detector array for the SWIR channels (actively cooled down to 150 K and thermally controlled to 0.1 K). A spectral resolution of at least 10 nm will be achieved over the broad spectral range from 420 nm up to 2450 nm with a VNIR (96 spectral channels) and a SWIR (136 spectral channels) detector. The overlapping range from 900 nm to 1000 nm will enable the processing chain to improve the atmospheric correction by resolving the water absorption band around 950 nm with sufficient signal to noise performance which is, e.g. 500 at 495 nm and 150 at 2200 nm. The data acquisition of the two spectrometers is realized with the method of in-field separation utilizing two entrance slits. This leads to a time separation of 88 msec between the VNIR and SWIR channels and means that the SWIR instrument scans the same area on ground about 20 lines delayed with respect to the VNIR instrument (a small

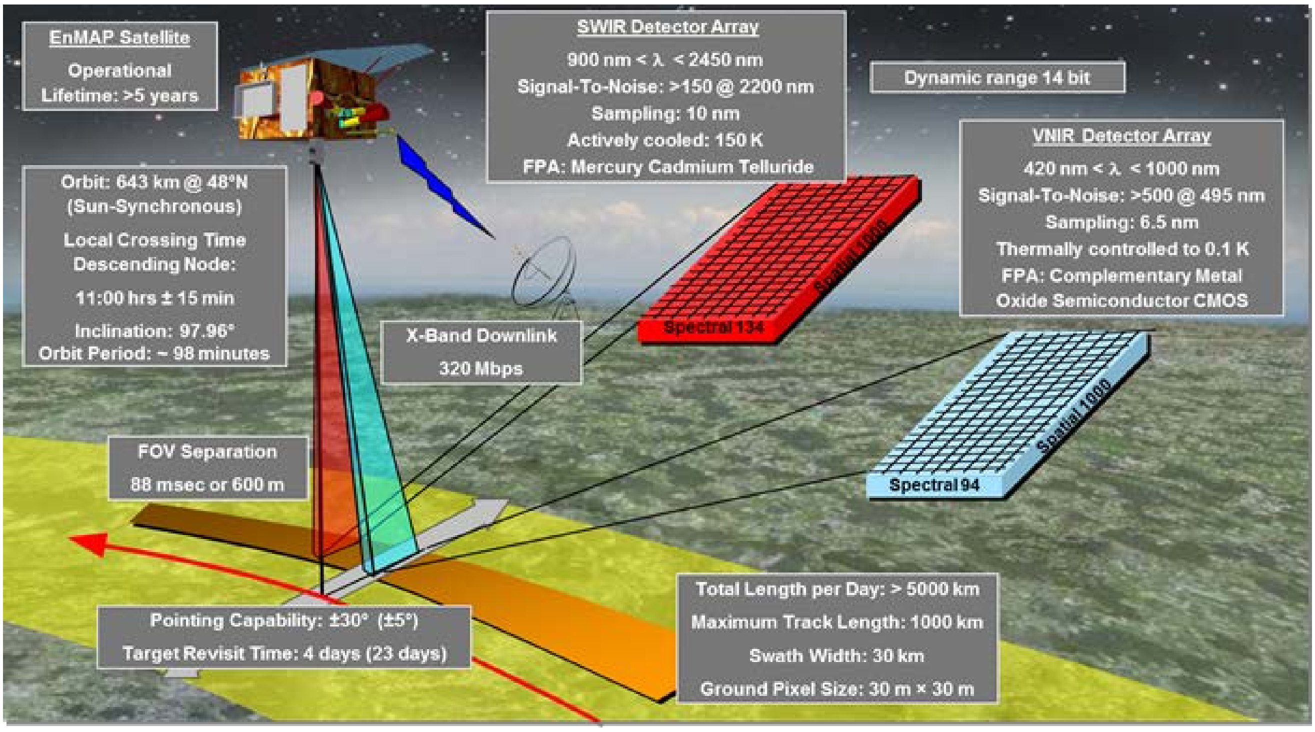

**Figure 1 Mission performance parameters**

latitude dependent offset will be noticed in across direction due to the earth rotation). Therefore an increased effort in geometric processing is necessary in order to be better than the required co-registration accuracy of 0.2 pixel size. Based on the advanced spectrometer design keystone and smile effects can be neglected, but will be recognized in the processing chain.[16].

The satellite position is determined by GPS at 1 Hz. Beside the master Star Tracker two slave Star Trackers also at 1 Hz together with two gyros at 10 Hz serve for the satellite attitude determination during image acquisition.

The design of the HSI instrument provides a suite of technical tools and modes to perform measurements for the on-orbit calibration [5], which are in particular

- Shutter / calibration mechanism for dark value and calibration measurements
- Full aperture diffuser for sun calibration for absolute radiometric calibration
- Main radiometric sphere (white Spectralon) for relative radiometric assessment
- Secondary sphere (doped Spectralon) for spectral calibration assessment
- Focal plane LED for the characterization of non-linarity and for stability check

A series of measurement cyclograms are defined for the on board calibration measurements. Calibration measurements are performed periodically or with highest priority on request.

The ground segment is subdivided into three parts and comprises the following systems [6]:

- The mission operations system responsible for commanding and controlling the satellite and instrument.
- The payload ground system responsible for data reception, handling, archiving and delivery as well as for the user interfaces for observation and product orders.
- The processor, calibration and product quality control responsible for instrument in-flight calibration, establishment of an automatic processing chain and product quality assurance.

## III. PRODUCT GENERATION

The operational processing chain will be integrated into the Data Information and Management System DIMS at DLR, which provides a multi-mission processing, archiving and distribution facility for earth observation products [15]. For the purpose of processor development, verification and validation an identical processing chain under version control will be operated independently during the whole mission life time. Figure 2 shows the overview of the processing chain.

### A. *Transcription Processor*

The transcription processor generates internal products (not available for the users) and mainly collects the information from the different data streams, screens the image and housekeeping data quality, tiles the data take, annotates the tiles with quality and search information and archives the raw data product. The hyperspectral image data, which are downlinked via X-Band to the DLR receiving station in Neustrelitz (north of Germany), are first de-compressed and the dark current measurements - acquired before and after each data take sequence - are extracted and stored separately as dark current product for calibration and monitoring purposes. In case of earth observation the data take (up to 1000 km track length) are tiled to a size of 1000x1024 (approximately 30x30 km²). Only these tiles are long-term archived, whereas higher level products are produced only on demand. In case of in-flight calibration measurements (e.g. full aperture sun diffuser, deep space, internal lamp or LED measurements) are evaluated, interpreted and additional calibration information is derived. Data quality is monitored within a screening process, which extensively uses the information of the housekeeping data. Quality masks and measures are derived – e.g. bad or suspicious pixels, cloud and haze mask, water-land mask, image acquisition mode, image acquisition condition, corner coordinates and so on – and archived together with the image data, which finally provide advanced selection criteria for EnMAP image orders by the user community.

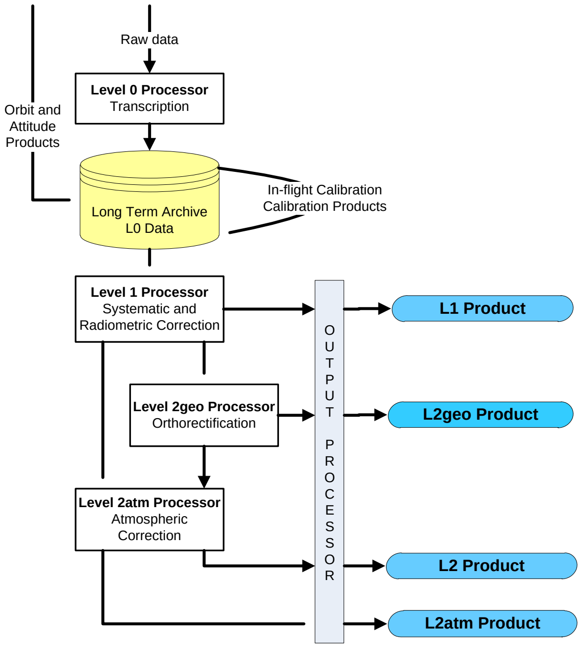

**Figure 2 EnMAP processing chain and product generation**

### B. *Systematic and Radiometric Conversion Processor (L1)*

The L1 processor corrects the raw HSI data for systematic effects and converts them to physical at-sensor radiance values based on the currently valid calibration tables. The correction includes the following sub-tasks

- Saturated pixel detection (including blooming with recovery)
- Suspicious pixel detection and dead pixel registration
- Non-linearity response correction (spatial and spectral direction)
- Electronic offset subtraction for the SWIR spectrometer (for the VNIR spectrometer the electronic offset is already internally corrected)
- Dark current subtraction, which is measured before and after each data take.
- Photo response non-uniformity (PRNU) correction (spatial and spectral direction, flat fielding)
- Spectral stray-light correction (spectral direction, deconvolution)
- Spatial stray-light correction (spatial direction, deconvolution)
- Smile correction including spectral resampling (spectral direction) (optional)
- Radiometric conversion towards at-sensor radiance values

Output products are the TOA radiance data cubes for the VNIR and SWIR instrument. Quality layers (e.g. bad pixel masks, land/water mask, cloud mask) and metadata (e.g. orbit and attitude measurements, geometric calibration values, spectral channel information) for further processing at the customer are attached.

### C. *Orthorectification Processor (L2geo)*

The EnMAP geometric processor produces ortho-images employing the technique of the rigorous model of Direct Georeferencing (DG) [8][9]. A linear pointing knowledge (independently in each of the two horizontal directions) of 100 m RMSE at nadir – corresponding to approx. 3 ground sampling distances - is specified for the EnMAP geometric accuracy. The error budget of the pointing knowledge is composed by the satellite position accuracy, which is estimated to be 18 m after post-processing at the ground segment, and by the attitude measurement accuracy of approximately 43 m on ground. A random error of about half a pixel size (approx. 15 m on ground) is assumed for the pixel boresight, whereas instrument boresight angles (e.g. thermal distortions caused by sun exposure during orbit revolution and seasonal effects, gravity release, vibrations by the reaction wheels and cooler compressor) are partly correctable after in-flight geometric calibration procedures.

The sensor internal geometry of the HSI will be extensively characterized in laboratory by highly accurate measurements of the look direction angles of about 20 single illuminated pixels (gravity center of the pixel) to the (adjusted) collimator axis. For each pixel the two angles on object side completely describe the internal camera geometry. This also includes (possible) geometric keystone effects. An accuracy of 1 arcsec for the measured angles is expected. The HSI mounting angles with respect to the attitude measurement system (body coordinate frame) are refined in the commissioning phase by geometric calibration procedures due to the gravity release and temperature influence. It is further foreseen to model the temperature dependence of these mounting (also called boresight alignment) angles, which is assumed to be a function of the sun exposure time of the satellite during orbit revolution. In order to minimize the temperature influence on the mounting angles as well as to increase mechanical stability the three star trackers are rigidly mounted on the HSI optical unit. The star tracker measurements are combined by Kalman filtering with the angular measurements of the inertial measurement unit. These (unit) quaternions are finally transformed from the Earth Centered Inertial frame (ECI) to the Earth Centered Rotated frame (ECR). The position measurements are interpolated (e.g. Lagrange interpolation) for each scan line of the HSI data cube, whereas the attitude measurements are approximated (e.g. Least Squares Splines or Chebyshev approximation).

Since the data acquisition of the two spectrometers VNIR and SWIR is realized with the method of in-field separation using two parallel entrance slits a difference in the viewing angles of approximately 0.05° occur which leads to an acquisition delay for the same location on Earth of 88 msec corresponding to 600 m on ground. As the satellite attitude changes slightly during this time a co-registration error between VNIR and SWIR data is obtained. In order to achieve the required co-registration accuracy of smaller than 0.2 pixel the reconstruction of the attitude for each scan line is based on approximation techniques leading to co-registration accuracies of about 0.1 pixel (in comparison using usual interpolation techniques values higher than 0.2 pixel are achieved) [7].

For the image orthorectification a global DEM database, fused from different sources like SRTM-C / SRTM-X / Tandem-X data, serves as input for the terrain correction process [13].

Finally a user selectable map projection system can be choosen (e.g. UTM with the zone derived from the center coordinates of scene as well as the neighboring zones, geographic projection). Within the map projection system image resampling is performed towards 30 m pixel spacing in case of UTM and 1 arcsec in case of Geographic projection. Different selectable resampling methods (e.g. nearest neighbor, bi-linear, cubic convolution) to generate the final orthorectified products are offered to the customer. The VNIR and SWIR data are independently orthorectified and finally merged to a consistent product.

The geometric accuracy of the orthorectification is crucial for overlaying the data with existing data sets, maps, or in geographic information systems (GIS) and using them for evaluations like change detection, map updating, and others like enhanced atmospheric correction using terrain information (see chapter of Atmospheric Correction Processor). Therefore an improvement of the sensor model shall be achieved by ground control points (GCP), which are extracted automatically from reference images of superior geometric quality using image matching techniques. In a first step tie points between the HSI uncorrected image and a reference image are determined by matching. In case optical data serve as reference an intensity based matching and an object based matching is applied. In case the DEM data (the same data base as used for the orthorectification with high quality horizontal geometric accuracy) serve as reference a shaded DEM model is calculated simulating the conditions that were prevailing during the HSI scene acquisition – namely the sun elevation and azimuth angles. Then tie points are determined by intensity based matching and / or multimodal matching based on similarity metrics like mutual information [14]. Complementing now the found tie points with interpolated DEM height values a set of full qualified GCP can be derived. In a second step the GCP sets serve as input to improve the LoS model parameters within a least squares adjustment process. Different levels of GCP outlier detection is included in the matching processes itself as well as in the least squares adjustment od sensor model parameters.

The feasibility of this approach to extract GCP from reference images for a refinement of the sensor model within an operational environment has been successfully demonstrated at different projects [3].

### *D. Atmospheric Correction Processor (L2atm)*

The EnMAP L2atm processor performs atmospheric corrections of the images employing separate algorithms for land and water applications. The choice of the land and/or water mode is defined by the customer. However, scenes may also be processed in both modes, e.g. for coastal areas or inland lakes that may contain a large percentage of land and water pixels.

Input for the atmospheric correction processors are the L1 product or the L2geo product, selectable by the customer. For the atmospheric correction over land a combined atmospheric and topographic processing is possible, which is only possible for scenes with accurate geometric correction. A geometric accuracy better than one pixel size is required for a combined topo / atm correction in order to avoid artifacts caused by the inaccurate registered DEM and orthorectified image.

#### *1) Land Applications*

Relevant criteria for the selection of a radiative transfer code with respect to the EnMAP mission are:

- spectral coverage of the radiative transfer calculations
- spectral resolution
- aerosol models
- treatment of gas absorption and multiple scattering

The MODTRAN-4 (moderate resolution atmospheric transmission) code covers the solar reflective spectrum (from 400 nm to 2500 nm) and even the thermal region. It supports a sufficiently high spectral resolution for the absorbing gases (water vapor, ozone, oxygen, carbon dioxide etc.). It also includes a rigorous treatment of the coupled scattering and absorption processes. Moreover, it offers a set of representative aerosol models (rural or continental, urban, maritime, desert). Therefore, MODTRAN-4 will be selected to compile a database of atmospheric correction look-up tables with a high spectral resolution of 0.6 nm to enable the processing of the 10 nm channel bandwidths of EnMAP. This “monochromatic” or fine spectral resolution database has to be resampled with the EnMAP channel filter curves. The advantage of compiling a “monochromatic” database is the possibility of quickly resampling it with updated spectral channel filter functions avoiding the necessity to run time-consuming radiative transfer calculations for the solar and view geometry pertaining to the acquired scenes.

The EnMAP image processing will be performed with the ATCOR (atmospheric correction) code that accounts for flat and rugged terrain, and includes haze/cirrus detection and removal algorithms [10][11]. Figure 3 shows an example of the atmospheric correction without and with haze removal.

Output products will be the ground reflectance cube, maps of the aerosol optical thickness and atmospheric water vapor, and masks of land, water, haze, cloud and snow.

**Figure 3 Example of an atmospheric corrected scene from ALOS/AVNIR-2 data with (top) and without (bottom) haze removal**.

### 2) *Water Applications*

A different strategy is employed for water applications exploiting the spectral properties of water, i.e. the low reflectance at wavelengths greater than 800 nm can be used to derive the aerosol map required for the retrieval of the map of water leaving radiance. In case of specular reflection (so-called “sun glint”) on water bodies, certain parts of the scene are contaminated with the glint signal. The glint signal can be removed to enable an evaluation of the water constituents in these areas. A distinctive, physical feature of remote sensing of water objects is that visible (and partial near infrared) radiation penetrates the water body and is reflected back in the direction of the sensor not only by the water surface, but also by deeper water layers. In this context, the radiative transfer model for processing of remote sensing water scenes should allow for the coupled treatment of radiation propagation in both atmosphere and water media.

A number of radiative transfer codes allow for a coupled treatment of radiation propagation in atmosphere and water. One of the most widely applied of these is the finite element method. This method provides the possibility to obtain radiation intensities in all polar and azimuthal directions and it demonstrated better performance in the case with highly peaked phase functions, which are typical in the atmosphere and natural waters. In order to be used in an image processing system, the radiative transfer code has to be supplemented by optical models of the atmosphere and water media. In particular, the MIP (Modular Inversion Program) is used, which combines the finite element method with the MODTRAN4 atmospheric model and the multi-component water model [2].

Output products are the water reflectance cube, water constituents, the aerosol optical thickness map and updates of masks of land, water, haze and cloud.

## IV. INFLIGHT CALIBRATION

Inflight calibration refers to all measurements and data analyses aiming to assess radiometric, spectrometric and geometric characteristics of the EnMAP hyperspectral instruments in orbit. The HSI will undergo extensive characterization and calibration measurements before launch and re-calibrated after launch by updating the calibration tables.

The dark value measurements for all spatial and spectral pixels will be carried out at begin and end of each data take by closing the entrance slit with the shutter mechanism. Deep space looking with opened shutter serves as verification measurement especially in the SWIR channels.

Sun calibration measurements are used for absolute radiometric calibration of the HSI in orbit. To this end the full aperture diffuser is moved into the entrance aperture of the telescope and the satellite is oriented for the measurement of the extraterrestrial sun irradiation via the diffuser.

For the relative radiometric calibration light sources inside the main sphere are operated at different currents, which illuminate the entire entrance slit. This kind of measurement only allows checking for the radiometric stability.

The spectral calibration in orbit is carried out using the secondary (smaller) sphere coated by doped Spectralon, which realizes absorption features.

Linearity measurements will be performed by changing integration times, where different light sources can be used.

Geometric calibration uses ground control information derived from orthorectified scenes of superior geometric quality (especially high resolution sensors), maps and other available sources. The test sites are distributed over a broad range of latitudes to account for thermal influences.

## V. INSTRUMENT MONITORING

Instrument monitoring takes a broader view on functioning of the instrument in-orbit by analyzing essential housekeeping data (e.g. temperatures, voltages) in addition to the results of calibration on a long-term basis. Monitoring analyzes changes and trends in instrument behavior, which might indicate problems and joins all available information for synoptical analysis and is therefore closely linked to instrument calibration. The monitoring of the instrument calibration (dark values, relative and absolute radiometric calibrations, spectral calibrations) is based on time series of main parameters for trend and statistical analysis. Additionally the instrument status information will be monitored and documented

- temperature of functional units like optical bench and focal plane
- voltages and currents from the secondary power supply like for the lamps and detectors
- instrument operational status like integration times and shutter operations
- life limited resources like burning time of the lamps and exposure time of the diffuser

## VI. VALIDATION AND QUALITY CONTROL

Validation is mainly the process of assessing, by independent means, the quality of data products as defined by the Committee of Earth Observation Satellites CEOS. The validation activities are under lead and coordination of GFZ Potsdam. For the validation of radiances an international team is foreseen. The Quality Control [1] is a systematic and continuous data product verification, which includes

- band-to-band correlations and co-variances
- image striping
- pixel, line, band failures
- saturation effects (blooming)
- image noise
- products of different levels for correctness

## VII. CONCLUSION

The automatic processing chain for product generation of the future spaceborne hyperspectral imager EnMAP is presented as far as the design is fixed at the current state of Phase C. Only minor changes will be expected for the upcoming phases (implementation, test, verification and validation). High level products will be derived and delivered to the international user community. Extensive radiometric, spectral and geometric characterisation and calibration will be performed before launch as well as in-flight calibration during the whole mission.

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