ENMAP - THE FUTURE HYPERSPECTRAL SATELLITE MISSION PRODUCT GENERATION

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ABSTRACT:

The basic components of the future German satellite mission EnMAP (**En**vironmental **M**apping and **A**nalysis **P**rogram) are the project management led by the Space Agency of the German Aerospace Centre (DLR) located in Bonn-Oberkassel, the space segment consisting of the satellite bus and the hyperspectral instrument established by Kayser Threde in Munich and OHB-Systems in Bremen, the science advisory group headed by GFZ (Deutsches GeoForschungsZentrum) and the ground segment led by DLR. The ground segment is responsible for the establishment of missions operations (e.g. satellite and instrument control), provision of the payload ground segment services (e.g. data reception, operational processing, archiving, user interfacing, product handling) and development of the processor/calibration/validation (PCV) system. This paper describes briefly the EnMAP mission, the mission objectives, the instrument and satellite bus characteristics, the ground segment structure and mainly addresses the concept and activities within the PCV sub-system, which is responsible for the generation of high quality hyperspectral data products.

1. INTRODUCTION

The future German satellite mission EnMAP (**En**vironmental **M**apping and **A**nalysis **P**rogram) addresses hyperspectral remote sensing (Müller, A. et al., 2006; Kaufmann, H. et al., 2006; Stuffler, T. et al., 2007) with the major objectives to measure, derive and analyse diagnostic parameters for the vital processes on Earth's land and water surfaces. Standardized products will be generated and delivered to the international user community of science and industry coordinated by GeoForschungsZentrum Potsdam GFZ as the mission principal investigator (Kaufmann, H. et al., 2009). The major components of the EnMAP project are: project management by the Space Agency of the German Aerospace Centre (DLR), space segment by Kayser Threde GmbH (hyperspectral instrument; satellite bus by OHB-Systems) (Stuffler, T. et al., 2009), science advisory group headed by GFZ and ground segment realized by DLR. The ground segment comprises (Müller et. al., 2009):

- The mission operations system 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 calibration, processing chain, and validation system capable of calibrating the sensor, generating calibrated hyperspectral data products at several processing levels, and validating these products.

The Applied Remote Sensing Cluster CAF at the German Aerospace Center DLR has long lasting experiences in the field of airborne and spaceborne data acquisition, processing, and analysis of hyperspectral images. In close collaboration with the German Space Operations Centre GSOC of DLR the CAF is responsible to establish the EnMAP ground segment.

1.1 Mission Objectives and Parameters

The major objectives of the EnMAP mission are to measure and analyse quantitative parameters describing environmental key processes of land and water surfaces. Derived geochemical, biochemical and biophysical parameters serve as input for physically based ecosystem models and ultimately provide information reflecting the status and evolution of various terrestrial ecosystems. Applications comprise agriculture, coastal zones, land degradation, geology and forest themes.

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 each 21 days under defined illumination conditions (sun-synchronous orbit at 653 km) and will contain as payload two pushbroom imaging spectrometers (VNIR: visual and near infrared and SWIR: short wave infrared). During the five years of mission operations, which are planned to start in 2013 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 instruments will be designed and realized by Kayser-Threde GmbH as 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. Data acquisition of the two spectrometers will have a time separation of 88 msec, which requires increased effort in geometric co-registration better than 0.2 pixel size. A spectral resolution of at least 10 nm will be achieved over the broad 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. Based on the advanced spectrometer design keystone and smile effects can be neglected, but will be recognized in the processing chain.

1.2 Processing, Calibration and Validation Overview

At the ground receiving station processing starts with the collection of data from different sources, e.g. the hyperspectral instrument, star sensors, GPS and housekeeping data. The transcription processor derives additional information, e.g. the quality of the acquired data. The level 1 processor corrects the hyperspectral image for systematic effects of the focal plane detector matrix, e.g. radiometric non-uniformities, and converts the system corrected data to physical at-sensor radiance values based on the currently valid calibration values. The spectral and radiometric in-flight calibration is based on dark current measurements performed for each data take as well as by utilization of a full aperture diffuser plate and further calibration equipment, e.g. internal light sources. The level 2-geo processor creates orthoimages based on Direct Georeferencing techniques implementing a line-of-sight model, which uses on-board measurements for orbit and attitude determinations as well as the sensor look direction vectors based on the currently valid geometric calibration values. Furthermore it is foreseen to automatically extract ground control points from existing reference data sets of superior quality (e.g. the Image2006 database with about 10-20 m absolute geometric accuracy or Image2009 database to be generated or USGS ETM+ land cover dataset) by image matching techniques to improve the geometric accuracy better than one pixel size (Müller, R. et al., 2008). The geometric in-flight calibration is based on data takes combined with ground control points. Terrain displacements are taken into account by a global digital elevation model (e.g. derived from SRTM-C/X band, Tandem-X or ASTER). The level 2-atm processor performs atmospheric and haze correction of the images by estimating the aerosol optical thickness and the columnar water vapour separately for land and water surfaces. The model uses the radiative transfer equation and takes the date, the sensors' spectral response functions as well as view and solar geometry into account to convert physical at-sensor radiance values to surface reflectance values. In order to ensure the spectral, radiometric, and geometric accuracy of all EnMAP products they are periodically validated within time series and with data from other sources, e.g. field measurements.

2. ENMAP PRODUCT GENERATION

2.1 EnMAP Standard Product Definitions

The EnMAP products are derived from tiled data takes of size 1024x1024 pixels (~30x30 km²), which are generated by the processing system on demand and delivered to the user community. Different product definitions (e.g. CEOS, ESA or from satellite data providers) are in common use, but a coherent assignment of the foreseen EnMAP product types to these definitions is inaccurate. Therefore the EnMAP product definitions are specified as follows

At-Sensor-Radiance Product (L1)
The Level 1 product is radiometrically calibrated, spectrally characterised, geometrically characterised, quality controlled and annotated with preliminary pixel classification (usability mask). The auxiliary information (e.g. position and pointing values, interior orientation parameters, gain and offset) necessary for further processing is attached, but not applied.

Orthorectified Product (L2geo)
The Level 2geo product is derived from the L1 product and geometrically corrected (orthorectified) and re-sampled to a specified grid. Auxiliary data for further processing are attached, but not applied.

Atmospheric Corrected Product (L2atm)
The Level 2atm product is derived from the L1 product, atmospherically corrected and the data converted to ground surface reflectance values. Auxiliary data for further processing are attached, but not applied.

Orthorectified and Atmospheric Corrected Product (L2)
The Level 2 product is derived from the Level 2 geo product, atmospherically corrected and the data converted to ground surface reflectance values.

2.2 Processing Chain

An overview of the EnMAP automatic and operational processing chain is given in
Figure **1**.

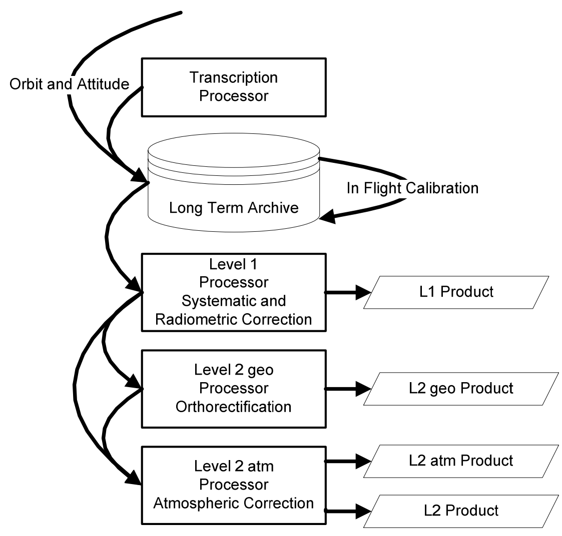

Figure 1 Processing Chain Overview

EnMAP level 0 (raw data) products will be long-term archived and not delivered to the user community, while level 1 (systematically and radiometrically corrected data), level 2 geo (geometrically corrected data), level 2 atm (atmospherically corrected data), and level 2 (geometrically and atmospherically corrected data) products will be processed on demand and delivered to the user without archiving. The processing chain will be fully automatic and integrated in the DLR's Data and Information Management System DIMS.

The design of the EnMAP processing chain is based on the experience with a fully automated and ISO 9001-2000 certified processing chain for airborne hyperspectral data (Bachmann, M. et al., 2007) as well as processing chains for spaceborne optical data (Schwind, P. et al., 2009). Similar to these processing chains, the newly developed EnMAP processors will include system calibration, orthorectification, atmospheric correction, and assessment of data quality (Storch, T. et al., 2008).

2.3 Data Transcription Processor

The transcription processor generates internal products (not available for the users) and mainly collects, pre-processes and archives the information from the different data streams necessary for subsequent processing as shown in Figure 2. The – via X-Band - down linked hyperspectral imager (HSI) data takes are first de-compressed (lossless compression), the dark current measurements are cut off (acquired before and after each data take sequence) and in case of earth image data takes (up to 1000 km track length) image tiles of size 1024x1024 (approximately 30x30 km²) are produced. 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 – namely bad or suspicious pixels, cloud and haze mask, water-land information and other derived metadata – and archived together with the image data, which provide effective selection criteria for EnMAP image orders by the user community.

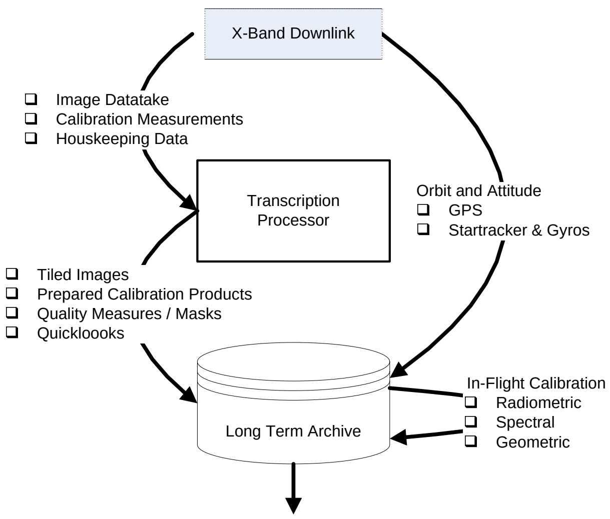

Figure 2 Transcription Processor

Complemented by pre-launch calibration and characterization the post-launch calibration analyses will deliver a detailed and quantitative assessment of possible changes of spectral, radiometric and geometric characteristics of the hyperspectral instrument, e.g. due to degradation of single elements the spectral, radiometric, and geometric behavior of the sensor vary within narrow limits during the complete mission lifetime. Hence, EnMAP can always achieve comparable measurements with respect to data from the same and from other calibrated missions. The transcription processor preprocesses the onboard calibration measurement and stores them in the long-term archive for subsequent and periodic evaluation by the operational in-flight calibration groups in order to generate valid calibration tables (e.g. radiometric, spectral, geometric, atmospheric tables).

The orbit and attitude products are preprocessed and refined by the Flight Dynamics Group of GSOC and ingested into the long-term archive for subsequent processing.

Internally the transcription processor uses parts of the Level 1 processor in order to derive quality parameters and quicklooks.

2.4 Systematic and Radiometric Conversion Processor

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. This part of the processing chain is illustrated in Figure 3.

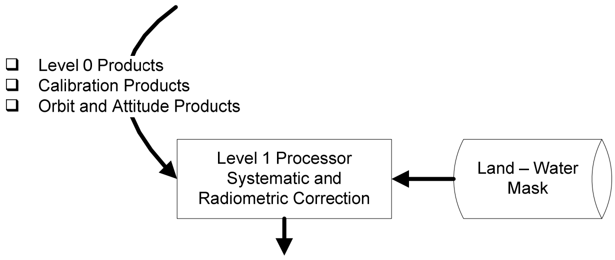

Figure 3 Systematic and Radiometric Correction

The correction includes the following sub-tasks

- Saturated pixel detection (including blooming with recovery)
- Bad, suspicious and dead pixel detection
- 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

2.5 Orthorectification Processor

The EnMAP level 2geo processor produces ortho-images applying the technique of Direct Georeferencing (DG). Figure 4 illustrates this part of the processing chain.

The Line-of-Sight model forms the basis of DG and utilizes on-board measurements of the star tracker systems and inertial measurement units combined by Kalman filtering for attitude determination, GPS (Global Positioning System) measurements for orbit determination (position and velocity), and sensor look

direction vectors derived from laboratory and/or in-flight geometric calibration.
Within an iterative process the intersection between the Line-of-Sight vector of each pixel (which also accounts for possible keystone effects) and the Digital Elevation Model is determined resulting in 3D points in object space.
Different map coordinate systems (e.g. UTM including ± 1 zone, geographic, universal polar stereographic) and different resampling techniques (e.g. nearest neighbor, bi-linear, cubic convolution) for the orthorectified products are offered to the customer (e.g. Müller, R. et al., 2005; Müller, R. et al., 2007) .
A linear pointing knowledge (independently in each of the two horizontal directions) of 100 m RMSE at nadir direction – corresponding to approx. 3 ground sampling distances - is specified for the EnMAP geometric accuracy. The satellite position accuracy is estimated to approximately 20 m after post-processing by the Flight Dynamics Group of GSOC and the attitude knowledge results in an uncertainty of approximately 55 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 by in-flight geometric calibration procedures.
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 2.6 Atmospheric Correction Processor). Therefore an improvement of the Line-of-Sight model shall be achieved by ground control points (GCP), automatically extracted from reference images of superior geometric quality using image matching techniques. Terrain displacements are taken into account by global digital elevation model (DEM) fused from different DEM data sets using quality layers. Figure 4 illustrates this part of the processing chain.

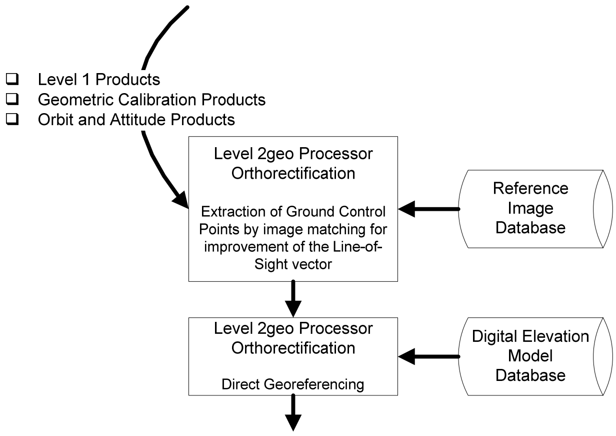

Figure 4 Orthorectification

An improvement of the Line-of-Sight vector with the help of automatic extracted GCPs by image matching is foreseen using global reference image databases. In order to automatically extract GCPs from reference images a hierarchical intensity based matching is performed (e.g., Lehner, M. and Gill, R. S., 1992). The matching process uses a resolution pyramid to cope with large image differences between the reference and the coarse registered image. The coarse image registration is performed by a geometric affine transformation of the L1 product using the corner coordinates derived from the a priori pointing knowledge. Based on the Foerstner interest operator, pattern windows are selected in one of the images and located with an accuracy of about one pixel in the other image. This is done via the maximum of the normalized correlation coefficients computed by sliding the pattern area all over the search area. The search areas in the matching partner image are determined by estimation of local affine transformations based on already available tie points in the neighborhood (normally from a coarser level of the image pyramid). The approximate tie point coordinates are then refined to sub-pixel accuracy by local least squares matching. The number of points found and their final (sub-pixel) accuracy achieved depend mainly on image similarity and decrease with time gaps between imaging. Only points with high correlation and quality figure are selected as tie points, including cross checking by backward matching of all found points. The tie points belonging to the reference image are supplemented to 3D object points by interpolated DEM values. Finally the set of tie points is divided into GCPs for an improvement of the orthorectification and ICPs for quality assessment. The selection of GCPs is based on the requirement of equally distributed points over the scene with high quality figure. Within the next processing step the GCP information is used to estimate improved parameters for the line-of-sight model by least squares adjustment, including iterative blunder detection, which eliminates step by step GCPs with a residual greater than a threshold starting with the bottom quality GCP. This part of the processor can only be used, if an appropriate reference image is available.
Output products are orthorectified scenes with an expected geometric accuracy of less than 30 m linear RMSE values with respect to the reference images.

2.6 Atmospheric Correction Processor

The EnMAP level 2atm processor performs atmospheric corrections of the images employing separate algorithms for land and water applications. Figure 5 illustrates this part of the processing chain.

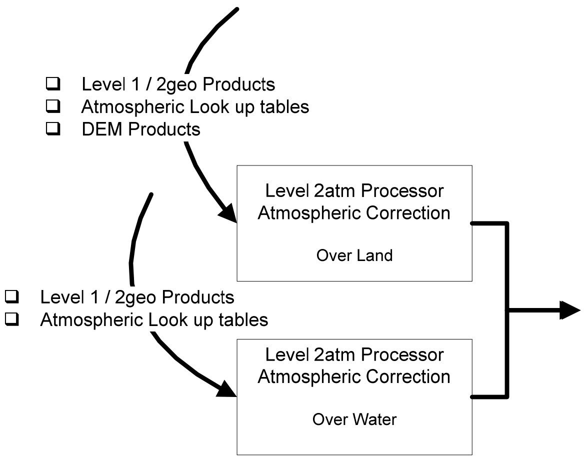

Figure 5 Atmospheric Corrections

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 requires accurate geometric correction with an accuracy less than one pixel size.

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 (e.g., Richter, R., 1996; Richter, R., 1998) that accounts for flat and rugged terrain, and includes haze/cirrus detection and removal algorithms.
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.

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 must be supplemented by optical models of the atmosphere and water media. In particular, the MIP (Modular Inversion Program) (e.g., Heege, T. et al., 2005) is used, which combines the finite element method with the MODTRAN4 atmospheric model and the multi-component water model.
Output products are the water reflectance cube, water constituents, the aerosol optical thickness map, and updates of masks of land, water, haze and cloud.

3. CONCLUSIONS

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 (ending with the critical design review in February 2010). Only minor changes will be expected for the upcoming phases (implementation, test, verification and validation).

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