PROCESSING CHAIN FOR THE FUTURE HYPERSPECTRAL MISSION ENMAP

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KEY WORDS: EnMAP, Satellite Mission, Hyperspectral Imaging, Processing Chain, Radiometric Correction, Geometric Correction, Atmospheric Correction

ABSTRACT:

The Applied Remote Sensing Cluster of the German Aerospace Center (DLR) is responsible for the establishment of the payload ground segment while the GeoForschungsZentrum Potsdam (GFZ) is in charge for the development of the science group and its activities for the future German hyperspectral satellite mission EnMAP (Environmental Mapping and Analysis Program), which is planned to be launched in 2012. EnMAP covers the electromagnetic spectrum from 420 nm to 2450 nm with a spectral resolution of at least 10 nm and a spatial resolution of 30 m × 30 m with a swath width of 30 km. The primary goal of EnMAP is to quantify and analyze diagnostic parameters describing key processes on the Earth's surface during the five years of mission operations. The main focus here is on the processing chain which will obtain standardized products including radiometric, geometric, and atmospheric corrections. Extensive calibration and validation activities are foreseen to achieve high-quality and consistent data with respect to the same and other missions.

1. INTRODUCTION

The Applied Remote Sensing Cluster (CAF) of the German Aerospace Center (DLR) and the GeoForschungsZentrum Potsdam (GFZ) both have long lasting experiences with the airborne and spaceborne data acquisition, processing, and analysis of hyperspectral images. Jointly with the German Space Operations Center the CAF is responsible for the establishment of the ground segment for the future German hyperspectral satellite mission EnMAP (Environmental Mapping and Analysis Program) (Kaufmann, H. et al., 2006; Müller, A. et al., 2006; Stuffler, T. et al., 2007).

1.1 EnMAP Mission

The major objectives of the EnMAP mission are to measure, derive, and analyze diagnostic parameters, which describe vital processes on the Earth's land and water sites. Those geochemical, biochemical, and biophysical parameters are assimilated in physically based ecosystem models, and ultimately provide information reflecting the status and evolution of various terrestrial ecosystems. Based on these quantitative measurements remote sensing standard products can be substantially improved and new user-driven information products will be generated, which could so far only be produced in the frame of scientific airborne hyperspectral campaigns. During the five years of mission operations, which are planned to start in 2012, EnMAP will provide information about the status of different ecosystems and their response to natural or man-made changes of the environment, which will be evaluated by an international user community of science and industry coordinated by the GFZ as the mission principal investigator (Kaufmann, H. et al., 2009). To meet these objectives a team of value adders and scientific partners jointly investigated the mission characteristics.

The EnMAP satellite will be operated on a sun-synchronous orbit at 643 km altitude to observe any location on the globe under defined illumination conditions featuring a global revisit capability of 21 days under a quasi-nadir observation. EnMAP has an across-track tilt capability of ± 30° enabling a revisit time of four days. The hyperspectral instrument (HSI) will be realized by Kayser-Threde GmbH as a pushbroom imaging spectrometer (Stuffler, T. et al., 2009). Its data acquisition over the broad spectral range from 420 nm to 2450 nm will be performed by a 2-dimensional CMOS (Complementary Metal Oxide Semiconductor) detector array for VNIR (visible and near infrared) with approximately 96 spectral channels, i.e. 10 nm spectral resolution, and by a 2-dimensional MCT (Mercury Cadmium Telluride) detector array for SWIR (shortwave infrared) with approximately 136 spectral channels, i.e. 10 nm spectral resolution, each with an analogue-to-digital converter resolution of 14 bits. The across direction of the arrays is used for the spatial resolution and the along direction for the spectral resolution. The ground pixel size will remain constant over the whole mission lifetime at certain latitude, e.g. 30 m × 30 m at nadir at 48° northern latitude. In this context a pointing accuracy of better than 500 m is expected, which will be improved to a pointing knowledge of better than 100 m by ground processing. The sensors' 1024 pixel in spatial direction results in a swath width of 30 km.

The EnMAP ground segment comprises (Müller, A. 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, processor chain, and validation system capable of calibrating the sensor, generating calibrated hyperspectral data products at several processing levels, and validating these products.

In this paper we focus on the processing chain for the EnMAP mission.

1.2 Overview of the Processing Chain

Figure 1. illustrates how the processing chain interacts with other mission elements in order to generate high-quality and consistent products.

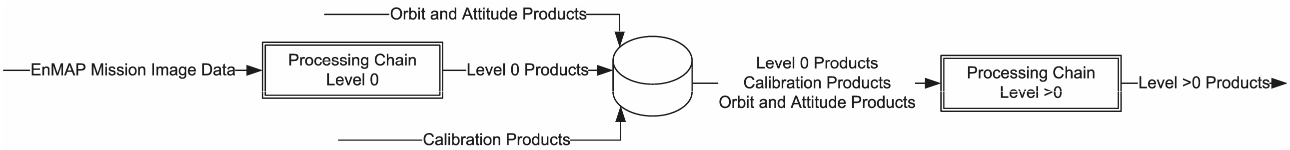

Figure 1. Processing Chain - Level 0

The EnMAP level 0 processor (see section 2.1) creates the EnMAP level 0 products, which are then stored for long term archiving along with the orbit and attitude as well as calibration products that are provided by the mission operations system and the calibration facility, respectively.

For the EnMAP level 1 to EnMAP level 2 product generation, the corresponding EnMAP level 0, calibration, orbit, and attitude products are retrieved to start the processing chain (see section 2). Image products will be sent periodically to the validation facility, which along with image data from other missions will carry out validation activities. The results of these activities will be reported to the calibration facility to inform of the possible needs to update the calibration products (Storch, T. et al., 2008).

1.3 Overview of the Product Level Definition

Table 2. illustrates that each organization or mission has, somehow, its own product level definition. Here the one of EnMAP is compared with the ones of CEOS and ESA.

	Product Description	CEOS	ESA	EnMAP
0	Raw data for instrument operating in observation mode at full space and time resolution with all supplemental information for subsequent processing (orbit, attitude and corrections for radiometric, spectral, geometric) computed and appended, but not applied.	Level 1a	Level 1a	not available for public
1	Data according to 0 not re-sampled, quality-controlled, radiometrically calibrated, spectrally characterised, geometrically characterised, annotated with satellite position and pointing, and preliminary pixel classification.	Level 1b	Level 1b	Level 1
2	Data according to 1 orthorectified and re-sampled to a specified grid.	Level 3	Level 1c	Level 2geo
3	Data according to 1 converted and not re-sampled to ground surface reflectance without terrain effects taken into account.	Level 2	Level 2a	Level 2atm
4	Data according to 2 converted to ground surface reflectance with terrain effects taken into account.	Level 3	Level 2a	Level 2

Table 2. Product Level Definition

2. PROCESSING CHAIN

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 processor chains, the newly developed EnMAP processors will include system calibration, parametric geo-coding, atmospheric correction, and assessment of data quality.

EnMAP level 0 products (raw data) will be long-term archived, while EnMAP level 1 (systematically and radiometrically corrected data), 2geo (geometrically corrected data), 2atm (atmospherically corrected data without geometric correction), and 2 (atmospherically corrected data with geometric correction) products will be processed and delivered to the user without archiving. The EnMAP level 0 processor mainly collects data from the different sources. Beside the datatake itself, it derives additional information, e.g. the quality of the acquired data. The EnMAP level 1 processor corrects the hyperspectral image for known effects, e.g. radiometric non-uniformities, and converts the system corrected data to physical at-sensor radiance values based on the corresponding valid calibration values and dark measurements. The EnMAP level 2geo processor creates orthoimages by direct georeferencing utilizing navigation data and an adequate digital elevation model. The extraction of ground control points from existing reference images by image matching techniques – if suitable reference images are available – serve to improve the line-of-sight vector and therefore to increase the geometric accuracy of the orthoimages. The EnMAP level 2atm processor converts the physical at-sensor radiance values to ground reflectance values separately for land and water applications. This includes the estimation of the aerosol optical thickness and the columnar water vapor. Figure 3. illustrates this part ("Processing Chain, Level > 0" of Figure 1.) of the processing chain.

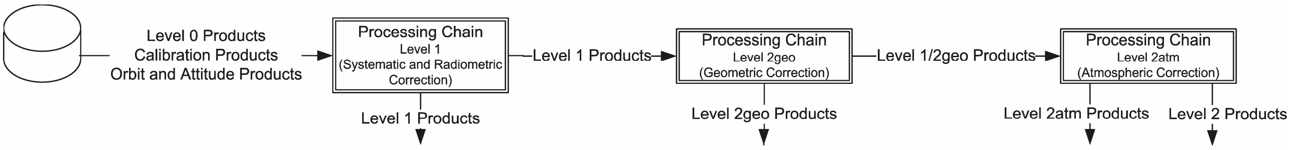

Figure 3. Processing Chain - Level >0

Two other spaceborne hyperspectral instruments are currently operated for civil Earth observation. These are the technical demonstration missions Hyperion on EO-1 by NASA/USGS (launched on November 21, 2000) and Chris on Proba by ESA (launched on October 22, 2001). While Hyperion/EO-1 distributes level 1 and level 2geo products, Chris/Proba provides level 1 products only.

2.1 Transcription

The EnMAP level 0 processor mainly collects information from the different data streams, extracts and interprets information, and evaluates and derives additional information, creating the EnMAP level 0 product. This EnMAP level 0 product comprises: Image tiles (Earth and for calibration purposes, namely for sun, deep space, and various internal lamps measurements), bad pixel/line/channel information, quicklooks, cloud and haze information, water-land information, metadata, and dark current measurements before and after a datatake sequence.

Complemented by pre-launch calibration and characterization the post-launch calibration analyses will deliver a detailed and quantitative assessment of possible changes of spectral and radiometric 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.

2.2 Systematic and Radiometric Corrections

The EnMAP level 1 processor corrects the HSI image data for known systematic effects like odd-even and non-uniformity, and then the processor converts these system corrected HSI image data to physical at-sensor radiance values based on the corresponding valid calibration and dark current values. The EnMAP level 1 product comprises: Image, bad pixel/line/channel mask, cloud and haze mask, land-water mask, metadata, processed orbit and attitude, and dark value information. Figure 4. illustrates this part ("Processing Chain, Level 1" of Figure 3.) of the processing chain.

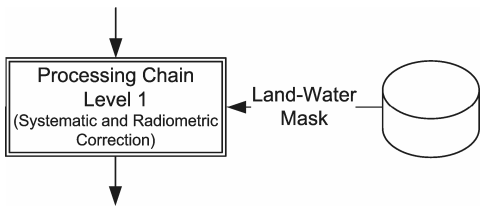

Figure 4. Systematic and Radiometric Corrections

The following steps are performed to generate physical at-sensor radiance values based on the raw data:

1. Saturated pixel detection (including blooming and recovery)
2. Bad and dead pixel detection
3. Non-linearity correction (spatial and spectral direction)
4. Offset subtraction (for SWIR and not for VNIR)
5. Dark current subtraction
6. Photo response non-uniformity correction (spatial and spectral direction, flat fielding)
7. Spectral stray-light correction (spectral direction, deconvolution)
8. Spatial stray-light correction (spatial direction, deconvolution)
9. Smile correction including spectral resampling (spectral direction) (optional)
10. Radiometric conversion (independent of spatial and spectral direction)

The Keystone correction (spectral direction) is part of geometric corrections since for radiometric corrections no resampling shall be applied.

2.3 Geometric Corrections

The EnMAP level 2geo processor produces ortho-images applying the technique of Direct Georeferencing. The line-of-sight model uses 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. An improvement of the line-of-sight model can be achieved by automatic extraction of ground control points (GCP) using image matching techniques with reference images of superior geometric quality. Terrain displacements are taken into account by global digital elevation model (DEM) fused from different DEM data sets using quality layers. Figure 5. illustrates this part ("Processing Chain, Level 2geo" of Figure 3.) of the processing chain.

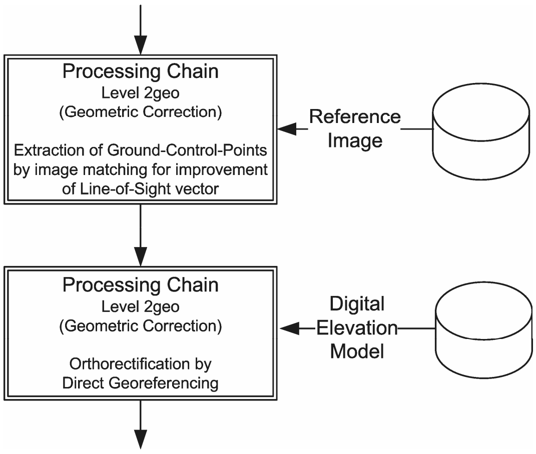

Figure 5. Geometric Corrections

The accuracy of this rectification result 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. Therefore, first an improvement of the line-of-sight vector with the help of automatic extraction of GCPs by image matching is foreseen. In order to automatically extract GCPs from the reference image 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. 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. 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.

The basis for all direct georeferencing formulas is the co-linearity concept, where the coordinates of an object point $\mathbf{r}^{m}_{object}$ expressed in any Earth bound mapping coordinate frame are related to image coordinates $\mathbf{r}^{sensor}_{object}$ derived from the measured pixel position in the sensor's coordinate frame. The rigorous relationship between 2D image coordinates and 3D object coordinates is given by

$$\mathbf{r}^{m}_{object} = \mathbf{r}^{m}_{sensor} + s \cdot \mathbf{R}^{m}_{body} \cdot \mathbf{R}^{body}_{sensor} \cdot \mathbf{r}^{sensor}_{object}, \qquad (1)$$

where $\mathbf{R}^{body}_{sensor}$ denotes the rotation from the sensor to the body coordinate frame, which has to be calibrated, and $\mathbf{R}^{m}_{body}$ denotes the rotation from the body to a mapping coordinate frame, which is derived from the angular measurements. If GCPs from image matching are available, an additional boresight rotation matrix can be estimated for refinement. The interior orientation is described by mapping column values i to the sensor coordinate frame with the focal length c by

$$\mathbb{N} \to \mathbb{R}^3: \ i \to \mathbf{r}^{sensor} = (x_i^{sensor}, y_i^{sensor}, -c)^T. \qquad (2)$$

The scale factor s is determined by the intersection of the sensor pointing direction with a given DEM using an iterative process, which finally results in a 3D point in object space for each image pixel. After object point reconstruction within the mapping frame the coordinates are transformed to any desired map projection, where the resampling (applying nearest neighbor, bi-linear, or bi-cubic resampling) of the ortho-image proceeds (e.g. Müller, R. et al., 2005; Müller, R. et al., 2007).

2.4 Atmospheric Corrections

The EnMAP level 2atm processor performs atmospheric corrections of the images employing separate algorithms for land and water applications. Figure 6. illustrates this part ("Processing Chain, Level 2atm" of Figure 3.) of the processing chain.

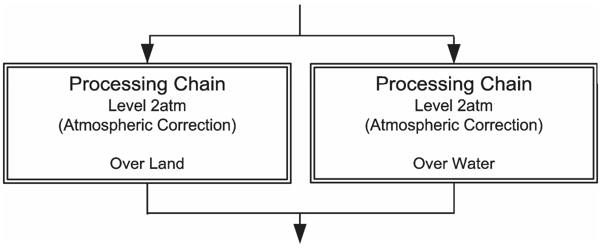

Figure 6. Atmospheric Corrections

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.

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 MODTRAN4 (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, MODTRAN4 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

An efficient processing chain is presented, which will be implemented for the future spaceborne hyperspectral imager EnMAP (Environmental Mapping and Analysis Program). Namely, it is pointed out how the high-level EnMAP products (including geometric and/or atmospheric correction) will be derived by the fully automated processing chain and how its components and the other mission elements interacts.

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