THE FUTURE SPACEBORNE HYPERSPECTRAL IMAGER ENMAP: ITS CALIBRATION, VALIDATION, AND PROCESSING CHAIN

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ABSTRACT:

The Applied Remote Sensing Cluster of the German Aerospace Center (DLR) is responsible for the establishment of the payload ground segment for the future German hyperspectral satellite mission EnMAP (Environmental Mapping and Analysis Program), which is planned to be launched in 2012. EnMAP covers the 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. To achieve high-quality and consistent data with respect to the same and other missions, extensive calibration and validation activities are foreseen during the five years of mission operations. The calibration results will be integrated in the processing chain to obtain standardized products, which include radiometric, geometric, and atmospheric correction. Here we focus on the following three aspects of the EnMAP mission: (a) analysis of data of the various calibration sources, (b) geometric processing with precise orbit and attitude data as well as atmospheric correction, and (c) supporting ground, airborne, and spaceborne campaigns to assess the quality of the output data delivered by the processing chain.

1. INTRODUCTION

The Applied Remote Sensing Cluster of the German Aerospace Center (DLR) has long lasting experiences with the airborne and spaceborne acquisition, processing, and analysis of hyperspectral images. Jointly with the German Space Operations Center it 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 (e.g., Van der Meer, F. D. and De Jong, S. M., 2006). 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 GeoForschungsZentrum Potsdam as the mission principal investigator. 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. 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 117 spectral channels, i.e. 5 nm spectral resolution, and by a 2-dimensional MCT (Mercury Cadmium Telluride) detector array for SWIR (shortwave infrared) with approximately 143 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

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better than 100 m by ground processing. The sensors' 1024 pixel in spatial direction result in a swath width of 30 km.

The EnMAP ground segment comprises:

- 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 calibration, processing chain, and validation for the EnMAP mission.

1.2 Overview of the Calibration, Validation, and Processing Chain

Figure 1. illustrates how the calibration and validation activities as well as the processing chain interact in order to generate high-quality and consistent products.

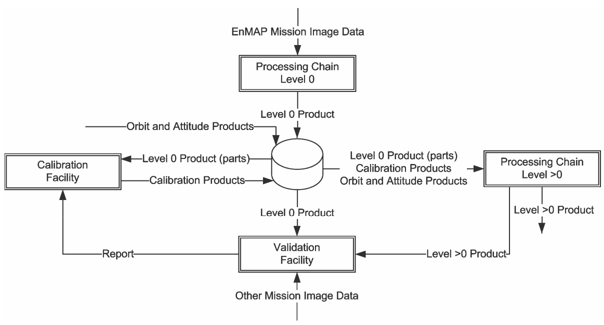

Figure 1. Calibration, Validation, and Processing Chain

The EnMAP level 0 processor (see section 3.1) creates the EnMAP level 0 products, which are then stored for long term archiving along with the orbit, and attitude products that are provided by the mission operations system. The calibration facility is in charge of creating and maintaining – if necessary – the calibration products (spectral, radiometric, and geometric). Therefore, it receives parts of the level 0 products, such as dark value, internal lamps, and sun measurements. (Due to the strong relation with its validation, the geometric calibration is described in section 4.2 while spectral and radiometric calibration is described in section 2.)

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 3). Image products will be sent periodically to the validation facility, which along with image data from other missions will carry out validation activities (see section 4.2). The results of these activities will be reported to the calibration facility to inform of the possible needs to update the calibration products.

2. CALIBRATION

During the complete mission lifetime the spectral and radiometric behavior of the sensor vary within narrow limits (e.g., Schwarzer, H. et al., 1998; Schwarzer, H. et al., 2003). However, the on-board calibration system allows processing of the data on ground to a spectral accuracy of better than 0.5 nm and radiometric accuracy of better than 5%. For this a full aperture diffuser mounted in front of the telescope is foreseen. Further calibration equipment, i.e. internal light sources, for frequent relative radiometric as well as spectral calibration measurements are installed in integrating spheres and coupled into the system via a calibration shutter mechanism located in front of the in-field separation unit. This mechanism also allows dark measurements before and after a data take sequence. Dark space calibrations will verify these dark measurements. 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 hyperspectral instrument, e.g. due to degradation of single elements. (See section 4.2 for geometric calibration and validation.) Hence EnMAP can always achieve comparable measurements with respect to data from the same and from other calibrated missions.

One of the tasks for calibration after launch is therefore to adjust the pre-launch and to establish the post-launch calibration reference for all essential measurement modes, i.e.

- Dark Value Measurements,
- Internal Lamps Measurements, and
- Sun Measurements.

The housekeeping data help to check the status and health of the HSI during calibration measurements and to correct for systematic effects, e.g. temperatures.

2.1 Dark Value Measurements

The measurement of dark values for all spatial and spectral pixels is the most frequent measurement to characterize the HSI. These values are needed both for control of the calibration as well as for the EnMAP level 1 processing of the data (see section 3).

The following dark value measurements will be performed during the whole mission lifetime

- at the beginning and end of each datatake of the Earth,
- at the beginning and end of each datatake of the internal lamps, and
- at the beginning and end of each datatake of the Sun.

These dark values are averaged from the single read-outs for each spatial and spectral pixel and then checked to be in a given range around the dark value reference. The averaged values are then used for dark value correction in further processing as well as for analysis of the internal lamp and Sun measurements. If outliers are found, they must be analyzed for possible causes, e.g. damaged pixel, spikes, and changes in the detectors' sensitivity.

2.2 Internal Lamps Measurements

The measurements of the several light sources inside the instrument will be operated at different currents and will illuminate the entire focal plane, but only a part of the optical path (starting with the entrance slit of the spectrometer) is used. The measurements allow checking for spectral and radiometric stability of the instrument or relative changes in the behavior of the focal plane. A measurement consists of dark value measurements and several illumination levels by the selected light sources. Each lamp has a certain burn-in time after voltage changes until it reaches the final light level. From all read-outs of one illumination level therefore a certain number of read-outs at the beginning have to be skipped. All other read-outs are averaged for each spatial and spectral pixel, corrected for dark values, and then compared to the reference values for the corresponding light source and illumination levels. The detailed analysis allows checking for sensitivity (slope) of all pixels, changes in pixel-related non-uniformity, and bad pixel recognition. Since the analysis always assesses the complete channel from the light source to the detector array, in general only a summarized characterization is possible and not a separated one for each single system component. In some cases such a single system component can be analyzed by investigating different measurements. If deviations from reference values are found, a more detailed analysis is necessary, possibly in connection with additional measurements, i.e. Sun calibrations. In the case that changes of a light source are found, which are stable and can be cross-proven from other measurements, the reference data for the corresponding internal lamp in the calibration product have to be updated.

2.3 Sun Calibration Measurements

The measurement of the Sun through a full aperture diffuser provides the only feasible opportunity for absolute spectral calibration of the HSI after launch. All other measurements only allow for a relative assessment. Assuming normal functioning and behavior of the instrument, a rather low frequency of Sun calibrations measurements is planned. Each Sun calibration measurement is planned to be accompanied by internal lamps measurements. To achieve the necessary accuracy, especially the geometry between the full aperture diffuser and the Sun during the measurement itself has to be known. Based on this information the part of read-outs with correct incident angle of the Sun can be selected. These measurements for all spatial and spectral pixels are used for averaging and calibration analysis. As long as all instrument's parameters are stable, the Sun measurements should be reproduced with a maximum deviation of 1%. If larger deviations are found, a more detailed analysis is necessary, including cross-checks with internal lamp measurements to verify causes and consequences of observed changes. If the changes can be proven, a corresponding update of the calibration product will be the consequence.

3. 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; Habermeyer, M. et al., 2005). Similar to this processor chain, 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), 2a (geometrically corrected data), 2b (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 (see section 2). The EnMAP level 2a 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 2b 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 2. illustrates this part ("Processing Chain, Level > 0" of Figure 1.) of the processing chain.

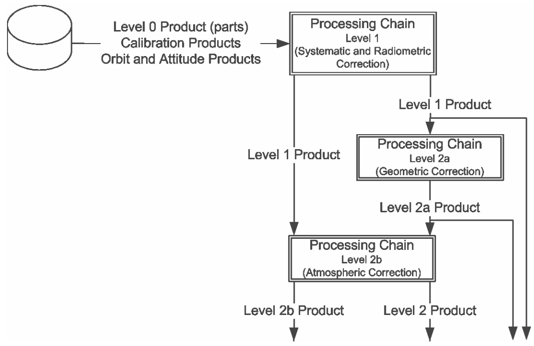

Figure 2. Processing Chain

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 2a products, Chris/Proba provides level 1 products only.

3.1 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 (for Earth, Sun, and deep space measurements), bad pixel/line/channel information, quicklooks, cloud and haze information, water-land information, metadata, and dark measurements (see section 2).

3.2 Systematic and Radiometric Correction

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 this system corrected HSI image data to physical at-sensor radiance values based on the corresponding valid calibration and dark values. The EnMAP level 1 product comprises: Image, bad pixel/line/channel mask, cloud and haze mask, water-land mask, metadata, processed orbit and attitude, and dark value information. Figure 3. illustrates this part ("Processing Chain, Level 1" of Figure 2.) of the processing chain.

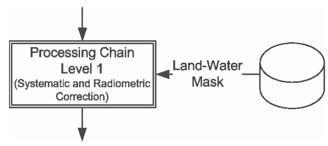

Figure 3. Systematic and Radiometric Correction

3.3 Geometric Correction

The EnMAP level 2a 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 4. illustrates this part ("Processing Chain, Level 2a" of Figure 2.) of the processing chain.

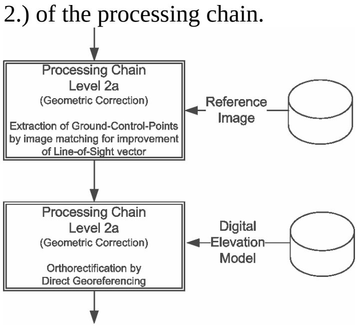

Figure 4. Geometric Correction

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

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

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

$$\mathbb{N} \to \mathbb{R}^3 : \; i \to \mathbf{r}^{sensor} = (x^{sensor}_{i}, y^{sensor}_{i}, -c)^T . \quad (2)$$

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).

3.4 Atmospheric Correction

The EnMAP level 2b processor performs atmospheric correction of the images employing separate algorithms for land and water applications. Figure 5. illustrates this part ("Processing Chain, Level 2b" of Figure 2.) of the processing chain.

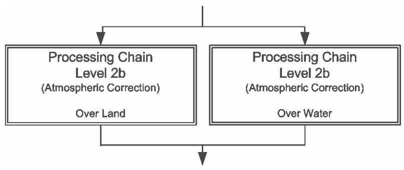

Figure 5. Atmospheric Correction

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 5 nm and 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.

4. VALIDATION

In addition to the usage of internal calibration sources and sun calibration, vicarious validation is an essential part of the validation during the whole mission time. After launch, vicarious validation is the only possibility to verify the link between the data acquired by the instrument and the data measured at the Earth's surface. A second topic is the verification of EnMAP level 1 and EnMAP level 2b products against reference measurements. Again vicarious validation is essential to detect sensor malfunction, calibration, and processing errors or insufficiencies.

In order to ensure the spectral, radiometric, and geometric accuracy of the EnMAP level 1, 2a, 2b, and 2 products, they are periodically validated within time series and with data from other sources and of superior quality (i.e., data from airborne hyperspectral instruments, spectroscopic field measurements).

Spectral/radiometric validation is conducted using repeated data acquisitions for well characterized and temporally stable areas and is further based on simultaneously acquired independent reference data measured in the field or using airborne spectrometers (e.g., Schroeder, M. et al., 2001; Teillet, P. M. et al., 2001). The in-flight geometric validation will assess the possible change of geometric parameters, e.g. the instrument or pixel boresight and the band-to-band registration of the VNIR and SWIR detector, by using ground control points and via the channels of the radiometric overlap region of the two sensors. These EnMAP calibration and validation activities are expected to be open for the support of the international user community.

4.1 Spectral and Radiometric Validation

For the validation of the EnMAP level 1 at-sensor radiance products, it is intended to use independent reference data (acquired by airborne sensors and/or by field instruments). These reference data sets (corrected to ground reflectances) will then be converted to top-of-atmosphere radiance values using atmospheric radiative transfer models. After that, the simulated level 1 data and the acquired EnMAP level 1 data will be analyzed, and a validation report will be written. In order to minimize the influence of the atmosphere, the reference site should be located in an environment with low atmospheric water vapor and dust load. Well known examples are Railroad Valley/Lunar Lake Playa (Nevada, USA) or Lake Frome (Australia).

Assuming that such test areas are stable over time, some analysis can take place without the need for field data taken exactly during the EnMAP data acquisition. In this case EnMAP data from two or more data acquisitions are analyzed and compared to each other in order to detect changes in system performance.

Also for the validation of EnMAP level 2 ground reflectance products independent reference data (acquired by airborne sensors or by field instruments) is required. In addition, an independently (offline) processed ground reflectance product will be generated using EnMAP level 1 data. After that, this independent reference data, this independently processed ground reflectance product, and the EnMAP level 2 product will be analyzed, and a validation report will be generated. The test sites for the validation of EnMAP level 2 products should include a variety of typical atmospheric conditions. Apart from spectral heterogeneity, there are no specific constraints on the sites and validation campaigns can be conducted together with other activities by DLR/GeoForschungsZentrum Potsdam like airborne hyperspectral campaigns or field spectroscopic measurements.

4.2 Geometric Calibration and Validation

Geometric processing of EnMAP scenes will be based on laboratory calibration, resulting in instrument to star-sensors alignment (instrument boresight) and pixel boresight (look angles/line-of-sight vectors of individual pixels), where both types of measurement are given for a range of temperatures to be expected under on-orbit conditions. In-flight geometric validation will periodically assess the possible change of these geometric parameters during satellite life time. This will be done via automatic image matching using orthoimages of superior quality of certain test sites. Test sites should be selected according to the stability of land-use patterns (arid regions with sufficient texture preferred). If the resulting shift vectors are larger than a given threshold or if they show a systematic behavior, it can be concluded that an update of the values for the geometric calibration parameters is necessary. Band-to-band registration of the VNIR and SWIR detectors can be checked via the channels of the radiometric overlap region of the two detectors. Image matching will be used to derive the shift vector pattern and corresponding statistics. The update of geometric instrument model parameters can be done via bundle adjustment using ground control points, which will be extracted via automatic image matching as mentioned before (see section 3.3). A generalized sensor model comprising e.g. focal length, principal point coordinates, sensor rotation, and sensor curvature of a geometric sensor array will be used. The initial parameters of this sensor model are derived from laboratory calibration (respectively, from corresponding valid geometric calibration values). Additionally, instrument/attitude boresight matrices will be estimated.

5. CONCLUSIONS

The efficient processing as well as the calibration and validation strategies are 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,
- how the high accuracy for these EnMAP products will be achieved over the whole mission's lifetime by the calibration and validation activities, and
- how all these components interact.

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