EnMAP Ground Segment Design: An Overview and its Hyperspectral Image Processing Chain

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Abstract EnMAP (Environmental Mapping and Analysis Program; www.enmap.org) is the first German hyperspectral remote sensing satellite mission. This chapter focuses on the challenges on the design of the ground segment as a whole and in particular of its image processing chain. In the context of the system response time we investigate the ability of tilting the satellite which allows for frequent revisits and enables meaningful downstream change detection activities on a global scale. In the context of comparable and high-quality controlled products we investigate in detail the processing steps to radiometrically calibrate, spectrally characterize, geometrically and atmospherically correct the data. The status corresponds to the baseline for the production activities of the ground segment, namely only minor changes are expected. The launch is planned for 2016. The establishment and operation of the ground segment is under responsibility of the Earth Observation Center (EOC) and the German Space Operations Center (GSOC) at the German Aerospace Center (DLR).

1 Introduction

The establishment and operation of the ground segment for the future hyperspectral satellite mission EnMAP (Environmental Mapping and Analysis Program; www.enmap.org) is under responsibility of the Earth Observation Center (EOC) and the German Space Operations Center (GSOC) at the German Aerospace Center (DLR). In July 2010, the ground segment has completed its design phase by

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successfully passing the critical design review. Now, it is in the production phase. The launch is planned for 2016. The EnMAP mission is the first German space-borne optical Earth observing mission (Stuffler et al. 2007).

The EnMAP satellite will be operated on a sun-synchronous orbit at 653 km altitude with a local time of descending node set to 11:00 h $\pm$ 18 min to observe any location on the globe under defined illumination conditions featuring a global revisit capability of 21 days under a quasi-nadir observation, namely with an across-track tilt of at most 5°. The satellite has an across-track tilt capability of 30° enabling a revisit time of four days (Stuffler et al. 2009). These revisit times hold in particular for equatorial regions, whereas, e.g. Munich, Germany, (48°N) can be revisited approximately every 2.5 days and for regions at the polar circles (66.5°) it is even approximately every 1.5 days. Beside for Munich, Germany, (48°N) Fig. 1 (top) illustrates the footprints of all potential acquisitions with an off-nadir angle of at most 30° for Mogadishu, Somalia, (2°N) and for Tromsø, Norway, (69.5°N) within one month. If quasi-nadir observations are considered only, the potential acquisitions decrease from 9 to 1 for Mogadishu, from 12 to 2 for Munich, and from 26 to 4 for Tromsø. Figure 1 (top) illustrates acquisitions of approximately 1,000 km length and it thereby also reveals that the footprints are different depending on the tilt necessary to hit the target area. This effect increases from the equatorial to the Polar Regions. Such frequent revisits allow for significant change detection activities on a global scale. Furthermore, the orbit allows acquiring areas between 82°N and 82°S under nadir conditions and between 85.5°N and 85.5°S utilizing the across-track tilt capability of 30°. There may be performance degradations for some smaller areas such as parts of Polar Regions or parts of regions affected by the South Atlantic Anomaly. For a ground track passing Munich Fig. 1 (bottom) illustrates the area which can be imaged utilizing an across-track tilt of 0° (corresponding to a field of view of ~30 km), at most 5° (corresponding to a field of view of ~150 km), and at most 30° (corresponding to a field of view of ~800 km) (Heiden et al. 2010). An acquisition of 90 km length is highlighted.

The major objectives of the EnMAP mission are to measure, derive, and analyze diagnostic parameters, which describe vital processes on the Earth's surface encompassing agriculture, forestry, soil and geological environments, as well as coastal zones and inland waters. 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 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 German Research Centre for Geosciences (GFZ) as the mission principal
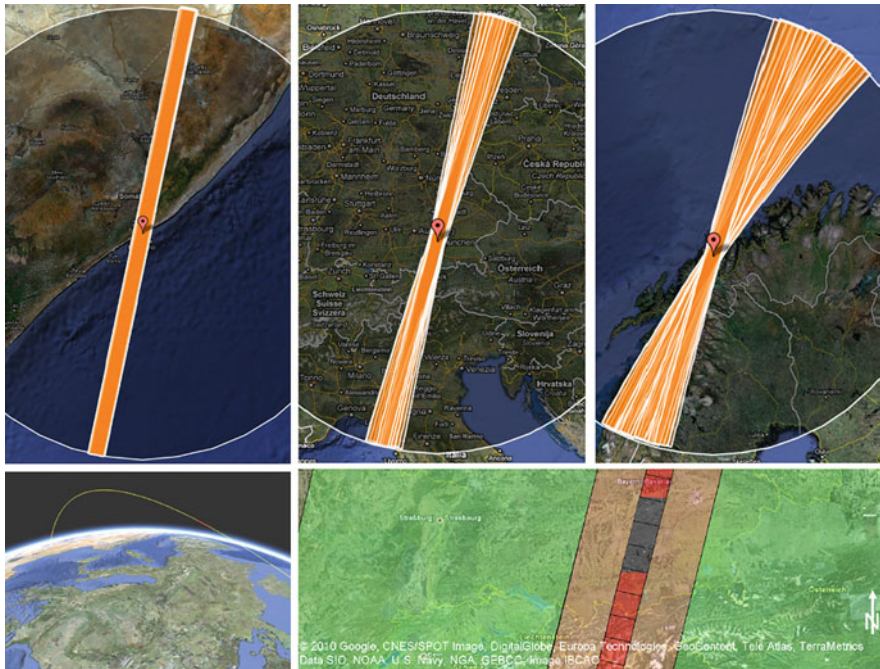
Fig. 1 *Top Left*: Potential acquisitions for Mogadishu, Somalia, (2°N) with an off-nadir angle of at most 30° and within one month. *Top Middle*: Potential acquisitions for Munich, Germany, (48°N) with an off-nadir angle of at most 30° and within one month. *Top Right*: Potential acquisitions for Tromsø, Norway, (69.5°N) with an off-nadir angle of at most 30° and within one month. *Bottom Left*: Orbit, where the satellite positions are marked red when the highlighted area illustrated at *bottom right* was imaged. *Bottom Right*: Map of Munich and southern Germany, where the area visible: (1) under nadir conditions is marked *red*, (2) within ±5° off-nadir angle is marked *red* and *orange*, (3) within ±30° off-nadir angle is marked *red*, *orange*, and *green*. The grid illustrate tiles of size $30 \times 30 \ km^2$

investigator. To meet these objectives a team of value adders and scientific partners jointly investigate the mission characteristics (Kaufmann et al. 2009).

The project management is led by the Space Agency of the German Aerospace Center (Rossner et al. 2009). The space segment consisting of instrument and bus will be established by Kayser-Threde GmbH (KT) and Orbitale Hochtechnologie Bremen-System AG (OHB System), respectively.

This chapter describes the EnMAP mission and focuses at first on the ground segment as a whole with its relations to the space and user segment and second on the image processing chain of the ground segment which includes geometric and atmospheric corrections as well as quality indicators. These indicators serve also as input for the quality assessment of higher-level products such as change detection maps, in particular of time series of products derived from hyperspectral data (Van der Meer and De Jong 2006).
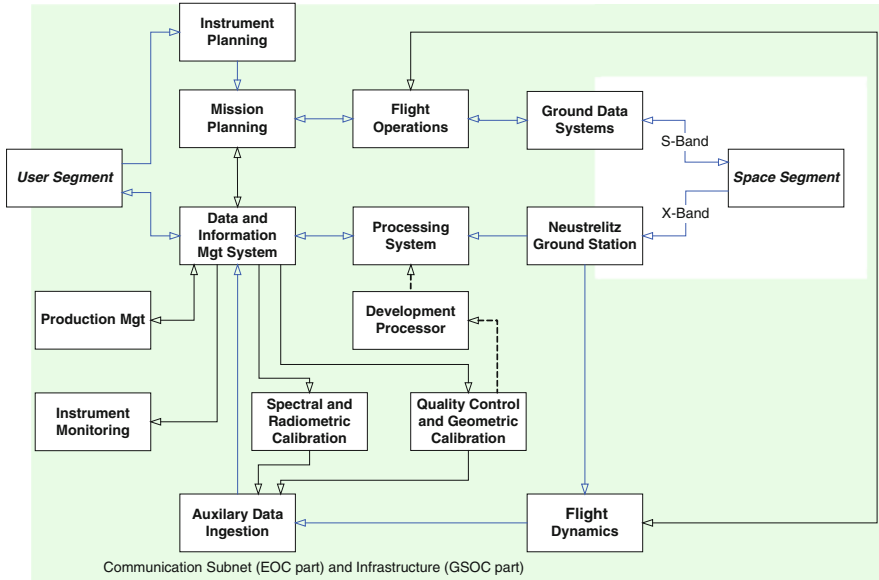
Fig. 2 Schematic illustration of ground segment

2 Ground Segment

The EnMAP ground segment is—beside its management part containing project managers, engineers, and product assurance—organized in three systems covering all aspects relevant to assure successful mission operations (Storch et al. 2010). The Mission Operation System, responsible for controlling and commanding satellite and instrument, is operated by the German Space Operations Center (GSOC) with its multi-mission control center in Oberpfaffenhofen, Germany, and its main S-band telemetry- and telecommand ground station in Weilheim, Germany. The Payload Ground System, responsible for data reception, data processing, and data archiving, as well as providing a web-interface to the EnMAP user community, is operated by the German Remote Sensing Data Center (DFD) with its multi-mission infrastructures located in Oberpfaffenhofen, Germany, and Neustrelitz, Germany, where also the main X-band payload data ground station is located. The Processor, Calibration, and Quality Control System, responsible for developing the hyperspectral processing system capable of generating high quality calibrated EnMAP data products at several processing levels, calibrating the sensor and validating the products, is operated by the Remote Sensing Technology Institute (MF) supporting the mission with its expertise and dedicated elements located in Oberpfaffenhofen, Germany, and Berlin, Germany. These three systems are further separated into 15 subsystems as illustrated in Fig. 2 (Müller et al. 2009).

Let us consider a routine scenario in the context of one of the major technical budgets of the ground segment which is—beside the product quality—the system response time. The system response time is defined as the maximal duration between the observation request put by a user and the delivery of the corresponding products to the user. The corresponding schematic workflow is marked blue in Fig. 2 starting and ending at the user segment. We subdivide the workflow when the scheduling of the observation requests is performed. Figure 3 illustrates the typical workflow for two observation requests (to be acquired within the same orbit, but not excluding each other) and corresponding up- and downlinks ending with the planning of the Timeline. Figure 4 illustrates the typical workflow beginning with the planning of the Timeline. Here, typical means that nominal operations are carried out and the segment is not in contingency operations. We do not consider the budgets concerning network throughput and network outage times here. All subsystems with exception of these for satellite control and commanding are designed such that network outage times of at least one week do not lead to loss of data (rolling archive with appropriate sizing). Thus, even longer outage times result in at most partial losses of "overflow" data. The network for satellite control and commanding is identified to be critical and therefore in particular redundant and leads to specific contingency operations.

Let us go into the details of Fig. 3. The S- and X-band ground stations communicate their availabilities (shown in blue) once a week for at least two weeks in the future. Based on this information and the observation requests submitted by a user, a planning of the subsequent Timeline is performed six hours before each S-band contact. The user can put her/his observation request in the time between the acceptance of her/his proposal (observation request #1) and at least 7 h before the S-band contact (observation request #2), where the corresponding acquisition has to be commanded. Since at least every 12 h an S-band contact is foreseen and the commanded Timeline covers up to 12 h, the user has to put her/his observation request at least 19 h before the (potential) acquisition. (The typical user is not informed about planned S-band contacts.)

Let us go into the details of Fig. 4. However, within the Timeline the two observation requests under consideration and subsequent S- and X-band contacts are scheduled (shown in blue). (Of course, the ground stations are informed about the planned S- and X-band contacts as well.) Data budgets detail that the planned S- and X-band contacts with a total duration of at least 30 min (for each band) each day are sufficient. Telecommands representing this Timeline are sent to the satellite and its telemetry is received via S-band. The loss of an S-band contact and link budgets are not considered here. At the computed moment of time the acquisition is performed. The orbit and attitude data covering an acquisition are received via X-band in the next contact whereas this cannot be assured for all channels of an image. But after 24 h the whole mass memory is dumped once (and the dump is performed by the "first in first out" principle). The loss of an X-band contact and link budgets are not considered here. At most 24 h after X-band downlinks the corresponding orbit and attitude products are generated and long-term archived. When these products and all channels of an image are available—
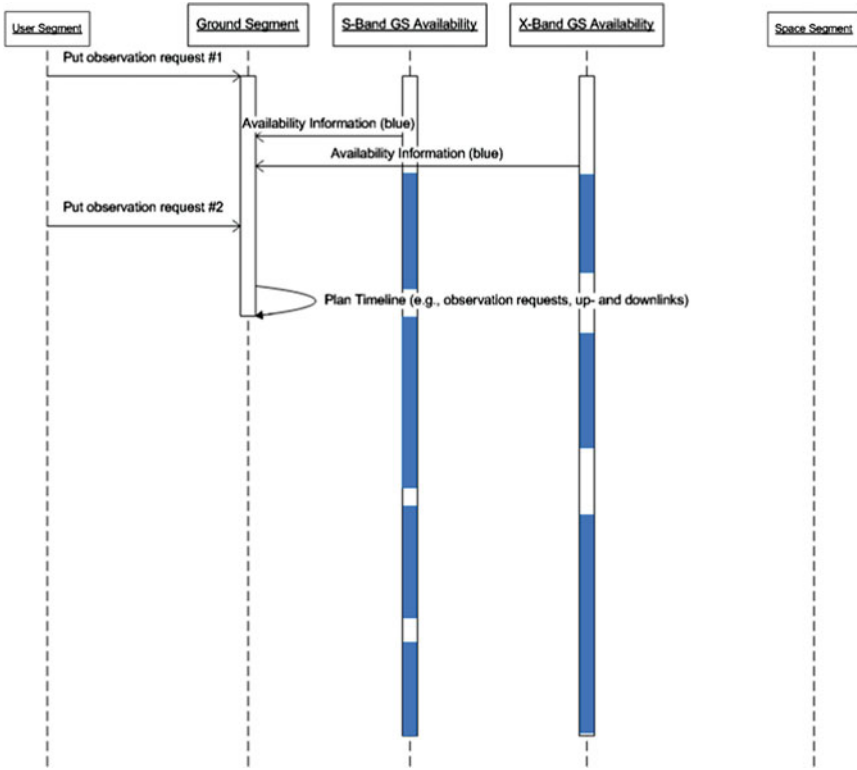
Fig. 3 Overview put observation request to planning of timeline

the calibration tables are already archived—, the archive products (Level 0) will be created. This is done in at most six days. The specific duration depends on the processors load due to the generation of products to be delivered (Level 1, Level 2). In at most four days the products to be delivered (Level 1, Level 2) are generated based on the archive products (Level 0) (Habermeyer et al. 2010).

We observe, that in particular the following subsystems are directly involved in image processing and the provision of auxiliary data (Storch et al. 2009):

- Communication Subnet (EOC part) and Infrastructure (GSOC part) connecting all subsystems via network.
- Data and Information Management System is a multi-mission facility which combines distributed archiving and dissemination of data products internally and also to the user segment through an online interface.
- Processing System generates archive products as well as spectral, radiometric, geometric, and/or atmospheric corrected hyperspectral images on an operational basis.
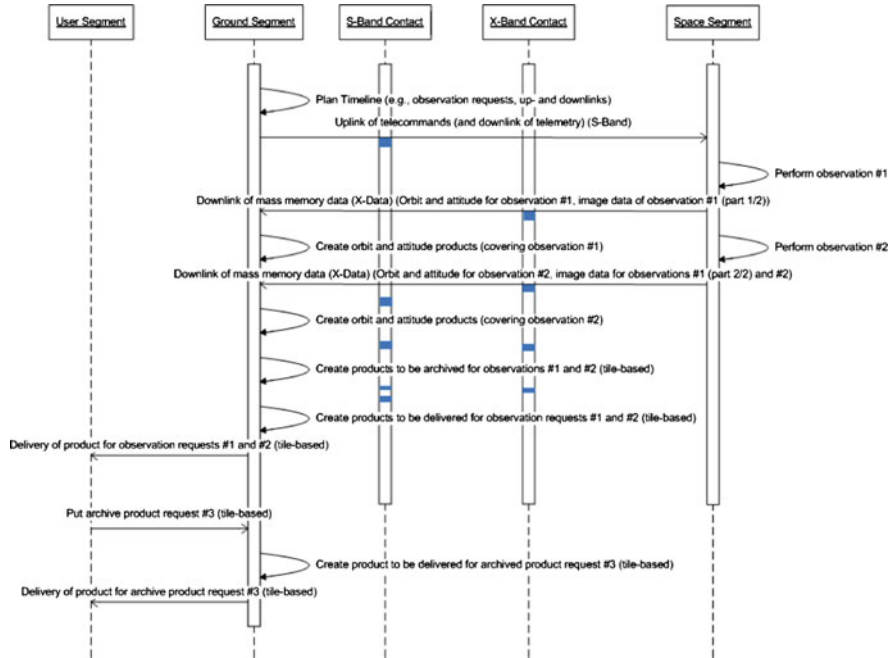
Fig. 4 Overview planning of timeline to delivery of products

- Auxiliary Data Ingestion collects all supplemental information for hyperspectral image generation such as spectral, radiometric, and geometric calibration and reference tables as well as orbit and attitude products.
- Spectral and Radiometric Calibration generates calibration and reference tables based on dark current measurements, measurements of internal sources such as lamps and Light-Emitting Diodes (LED), and Sun measurements for spectral and radiometric characterization and calibration.
- Quality Control and Ground Calibration generates geometric calibration and reference tables based on different on-ground measurements. Additionally the accuracy of all types of hyperspectral images is assessed to detect calibration or processing errors and quality information are added to the EnMAP products.
- Flight Dynamics comprises orbit and attitude determination as well as orbit prediction based on relevant on-board measurements such as data from the Global Positioning System and on-ground measurements such as ranging and angle tracking. Another aspect is the manoeuvre planning on a regular basis.
- Development Processor is used as a platform under versioning control for the development of the processing chain to be ingested in the Processing System (see above). It is described in detail in the next section.

3 Hyperspectral Image Processing Chain

The hyperspectral imager (HSI) will be realized as a pushbroom imaging spectrometer. Its data acquisition over the broad spectral range from 420 to 2,450 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. 6.5 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. 30×30 m^2 at nadir at 48° northern latitude. In this context a geographical accuracy of 100 m will be achieved for the image products which will be improved to 30 m with respect to a used reference image, if it exists, by ground processing. The sensors' 1,000 valid pixels in spatial across direction results in a swath width of 30 km (Mogulsky et al. 2009). An overlapping range from 900 to 1,000 nm between the VNIR and SWIR spectral channels 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 2,200 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 approximately 88 ms 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 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 (Müller et al. 2010).

Figure 5 shows an overview of the image processing chain (de Miguel et al. 2010). The **Level 0 (L0) Product** is always generated for long-term archiving in Data Information and Management System. It is only used for internal purposes and will not be available for external users. The following products will be generated on user request:

- **Level 1 (L1) Product**: it is radiometrically calibrated, spectrally characterized, geometrically characterized, 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
- **Level 2geo (L2geo) Product**: it is derived from the L1 product and geometrically corrected (correction of sensor, satellite motion and terrain related distortions) and re-sampled to a specified grid (orthorectified). Auxiliary data for further processing are attached, but not applied.
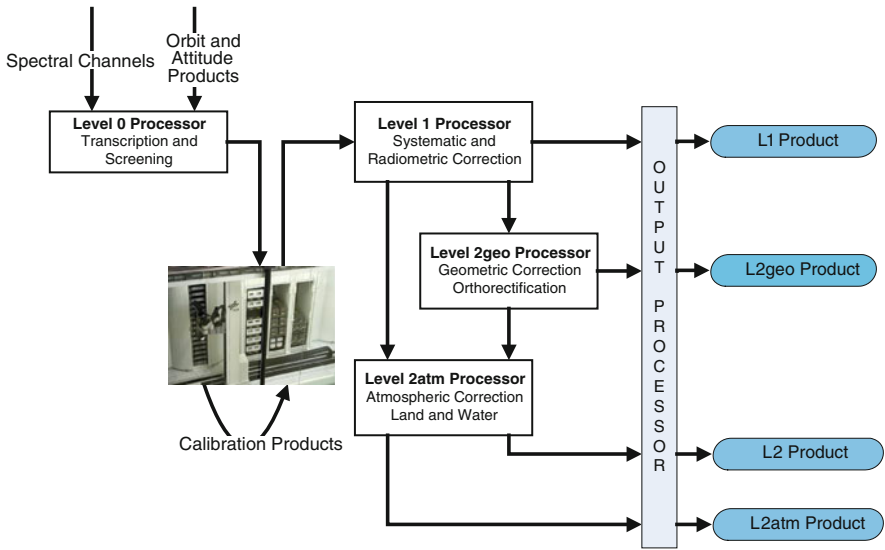
Fig. 5 Schematic illustration of image processing chain

- **Level 2atm (L2atm) Product**: it 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.
- **Level 2 (L2) Product**: it is derived from the Level 2geo product, atmospherically corrected and the data converted to ground surface reflectance values.

As product format for Level 1 and Level 2 the user can choose an image format of BSQ, BIL, BIP, JPEG2000, and GeoTIFF and the metadata format is always Extensible Markup Language (XML). A product report in portable document format (PDF) is appended to the product.

3.1 Level 0 Processor

Level 0 Processing for Earth and calibration data takes

1. collects the information from the different data streams,
2. screens the image and housekeeping (HK) data quality which includes unpacking and, if necessary, decompression of the data,
3. extracts, evaluates, and transcripts the available metadata to the XML format,
4. extracts and evaluates the calibration values which includes the separation of dark current measurements at the start and end of each datatake,
5. tiles the Earth datatake into parts of size $1{,}024 \times 1{,}024$ pixels as illustrated in Fig. 1 (bottom right), where the first and last 12 pixels of each line are also dark current measurements,

6. generates quick looks of Earth data takes in Joint Photographic Experts Group (JPEG) format which includes the execution of parts of the Level 1, Level 2geo, and Level 2atm Processors particularly for specific channels,
7. generates dead, suspicious, land-water, and cloud-haze masks for Earth datatakes,
8. annotates the tiles of Earth datatakes with data quality and search information, and
9. archives the raw data product.

The evaluations performed include in particular checks, if temperatures, voltages, currents, and pixel values are stable or in specified ranges and that the HK data are consistent.

3.2 Level 1 Processor

Level 1 Processing corrects the hyperspectral image data for known systematic effects. It also converts the system corrected image data to physical at-sensor radiance values based on the current valid calibration values and dark current information. The correction includes

1. flagging and screening of dead pixels based on corresponding calibration tables,
2. flagging of saturated (hot) and no-response (cold) pixels including removal of dark current measurements at the start and end of each line,
3. correction for non-linearities based on Look-Up-Tables (LUT),
4. correction for dark signal based on corresponding measurements at the start and the end of the datatake,
5. correction for stray light for the spectral and spatial direction,
6. correction for response non-uniformity (RNU),
7. gain matching for the VNIR detector since the low or high gain is automatically selected, namely low gain values have to be multiplied by gain matching coefficient to high gain values,
8. spectral referencing, where channels are assigned with wavelength information, namely with the center wavelength and the full width at half maximum (FWHM),
9. radiometric referencing since the data are finally stored in integer values with 16 bits and not as floating values used in the previous steps, and
10. annotation of data quality information in the form of reports or masks.

3.3 Level 2geo Processor

Level 2geo Processing applies the method of Direct Georeferencing (DG) to convert imagery into map-accurate forms by removing sensor, satellite motion, and terrain related geometric distortions from raw imagery. In particular for

change detection application this is one of the key issues to accurately overlay the image data with existing data sets or maps, namely for multi-source data integration or fusion. The physical method of DG is based on a Line-of-Sight (LoS) model, which extensively utilizes on-board measurements from Star Tracker Systems (STS), Inertial Measurement Units (IMU), Global Navigation Systems (GNS) as well as the geometric sensor characterization by laboratory and/or in-flight calibration. Also effects such as terrain displacements, speed of light, light refraction by the Earth's atmosphere, and Earth's rotation are considered. To achieve a co-registration accuracy of 0.2 pixels between the two spectrometers not only the absolute geometric error but also the relative geometric error during 88 ms is considered. While the pixels are registered concerning time by Level 0 and Level 1 processing, the pixels are registered concerning geometry by Level 2geo processing. The 4-step process of orthorectification consists of:

1. Direct Georeferencing Model

   a. Synchronization of attitude and position/velocity measurements with time tagged image lines using appropriate interpolation,
   b. Establishment of the LoS vector using the sensor's internal geometry, payload assembly geometry and time dependent satellite motion during image acquisition,
   c. Setting up the collinearity equation to relate locations of image pixels with an earth reference coordinate frame.

2. Digital Elevation Model (DEM) Intersection Model

   a. Projection of the DEM to the coordinate frame specified in the DG model,
   b. Interpolation of the DEM to generate a dense grid of height values appropriate for the orthorectification task,
   c. Connection of the DEM and LoS vector by an iterative procedure in order to retrieve object point coordinates for each image pixel.

3. Map Projection Model

   a. Transformation of the object points to a map projection like global systems, such as Universal Transverse Mercator (UTM) projection with World Geodetic System 1984 (WGS84) datum, or local system, such as the European Lambert Azimuthal Equal Area (LAEA) with European Terrestrial Reference System 1989 (ETRS89) datum. The projection can be chosen by the user.

4. Resampling Model

   a. Provision of different resampling techniques such as Nearest Neighbor, Bilinear, and Cubic Convolution, appropriate for processing. The resampling technique can be chosen by the user.

The geometric accuracy of the orthoimages derived by DG making use of the ORTHO code can be improved using Ground Control Point (GCP) information to

refine the parameter sets of the LoS model from approximately three Ground Sampling Distances (GSD) to one GSD. Image-to-image matching algorithms such as Intensity based Image Matching and Shaded DEM Matching permit the automatic extraction of GCP provided that existing orthoimages of superior geometric quality as global or local reference images are supplied.

Data quality information, like the Root Mean Square Error (RMSE) and residual plots, where Independent Control Points (ICP) serve as input, are annotated.

3.4 Level 2atm Processor

The Level 2atm Processing performs atmospheric corrections of the images employing separate algorithms for land and water applications. 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. The mode of correction "land and water", "land only", or "water only" can be chosen by the user.

In case of atmospheric correction over land, the Level 2atm Processor will make use of the ATCOR (atmospheric correction) code which takes into consideration flat and rugged terrain, and includes haze/cirrus detection and removal algorithms. Output products will be the ground reflectance cube, aerosol optical thickness and atmospheric water vapor maps, and land, water, haze, cloud and snow maps. Therefore, the six atmospheric functions path radiance, direct and diffuse transmittance ground-to-sensor, direct and diffuse solar flux and spherical albedo are considered. Aerosol type and optical thickness is automatically determined over land. Columnar water vapor is calculated using channels around 940 and 1,130 nm and appropriate reference or window channels around 880, 1,020 nm and 1,080, 1,240 nm, respectively. An optional combined atmospheric and topographic processing is possible for scenes with accurate geometric correction (geometric accuracy better than one GSD) where no artifacts caused by the inaccurate registered DEM and orthorectified image are present can be chosen by the user.

In case of atmospheric correction over water, the Level 2atm Processor converts the top-of-atmosphere radiance imagery into water bulk reflectance values in the visible interval. The processing includes: Sun glitter map generation by identification of specular reflection, namely sun glint, on water bodies, correction of water mask, cirrus detection and correction for all water pixels not covered with clouds and not affected by sun glitter, adjacency correction, retrieval of aerosol optical thickness, and atmospheric correction for all water pixels not covered with clouds and not affected by sun glint. Only the channels in the spectral region 420 to 900 nm are processed.

Data quality information, like land-water and haze-cloud-snow probabilities based on spectral criteria as well as the aerosol optical thickness separated for land and water, are annotated.

3.5 *Quality Control Activities*

With the advent of operational remote sensing services there is an increasing demand in highly reliable, well documented and standardized data products (Bachmann et al. 2010). In order to achieve this goal, operational data quality control (QC) and validation activities are essential. This comprises the documented quantitive assessment of geometric, radiometric, and spectral properties of data products (see also previous sections) to be provided to the user. By this process the valid function of the sensor and processing chain is investigated and thus ensured. In order to distinguish an anomalous from a nominal state of the instrument and processor, the uncertainty budgets related to the spectral, radiometric and geometric data product properties must be known. Therefore this data uncertainty analysis is also included within QC. This is one part of the operational processing chain in order to investigate the specific quality of a data product ordered by the user such as QC flag image (per-pixel quality measure) and the related metadata, but also contributions to the overall quality flag are generated. On a regular basis an additional interactive QC analysis will be carried out such as quantification of the signal to noise ratio and modular transfer function. This is necessary since certain properties can not be analysed in a fully automated way and these information will be provided to the user community.

4 Conclusions

This chapter illustrated that the design of the ground segment for the first German optical Earth observing spaceborne mission EnMAP (Environmental Mapping and Analysis Program; www.enmap.org) and in particular of its hyperspectral image processing chain is predestined to allow for meaningful downstream change detection activities on a global scale. Therefore, especially the system response time in combination with the frequent revisits and the comparable radiometrically calibrated, spectrally characterized, geometrically and atmospherically corrected products annotated with quality information were discussed. Activities planned to extend these considerations are the processing of simulated datatakes with a focus on its adequacy for downstream change detection purposes. Furthermore, it is planned to consider also if the system response time could be reduced and if sun glint correction could be supported. The status corresponds to the baseline for the production activities of the ground segment, namely only minor changes are expected. The establishment and operation of the ground segment is under responsibility of the Earth Observation Center (EOC) and the German Space Operations Center (GSOC) at the German Aerospace Center (DLR).

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