IMAGE PRODUCTS FROM A NEW GERMAN HYPERSPECTRAL MISSION ENMAP

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ABSTRACT

The upcoming Environmental Mapping and Analysis Program (EnMAP) - German imaging spectroscopy mission - is a joint response of German Earth observation research institutions, value-added resellers and space industry to the increasing demand for accurate, quantitative information about the status and evolution of terrestrial ecosystems. EnMAP is currently in the construction phase with a launch planned in 2019. The project management is led by the Space Agency of DLR. The space segment consisting of instrument and bus will be established by OHB System AG.

The EnMAP satellite will be operated on a sun-synchronous orbit at 643 km altitude with a local time of descending node 11:00 to observe any location on the globe under defined illumination conditions featuring a global revisit capability of 21 days under a quasi-nadir observation. The satellite has an across-track tilt capability of ± 30° enabling a revisit time of four days. The hyperspectral instrument will be realized as a pushbroom imaging spectrometer. Its data acquisition over the broad spectral range from 420 nm to 2450 nm will be performed by a CMOS (Complementary Metal Oxide Semiconductor) detector array for VNIR (visible and near infrared) with 95 spectral channels, i.e. 6.5 nm spectral resolution, and by a MCT (Mercury Cadmium Telluride) detector array for SWIR (shortwave infrared) with 135 spectral channels, i.e. 10 nm spectral resolution. The ground pixel size is 30 m × 30 m at nadir at 48° northern latitude. In this context a pointing accuracy of better than 500 m is expected. The pointing knowledge and therefore the accuracy of image products will be better than 100 m and can be improved by ground processing, if a reference image is available, to approximately 30 m (i.e. 1 pixel) w.r.t. the used reference image. The sensors' 1000 pixels in spatial direction result in a swath width of 30 km. Regular on-board calibration measurements are performed to update the calibration tables for the processors.

EnMAP level 0 (L0) image products (raw data) will be long-term archived while L1B products (systematically and radiometrically corrected data), L1C products (geometrically corrected data) and L2A products (atmospherically corrected data) will be processed on demand. The L1B processor corrects the hyperspectral image cube for systematic effects of the focal plane detector array, e.g. radiometric non-uniformities, and converts the system corrected data to physical at-sensor radiance values based on the currently valid calibration tables. The L1C processor creates ortho-images based on direct geo-referencing 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 calibration values. Furthermore, it is foreseen to automatically extract ground control points from existing reference data sets by image matching techniques to improve the geometric accuracy better than one pixel size. The L2A processor performs atmospheric correction and haze detection of the images by estimating the aerosol optical thickness and the columnar water vapor. Output products will be the ground reflectance cube and masks of land, water, haze, cloud and snow.

KEYWORDS: hyperspectral, sensor, mission, remote sensing, image product, calibration

INTRODUCTION

The Earth Observation Center (EOC) of DLR has long lasting experiences with the airborne and spaceborne acquisition, processing, and analysis of optical image data. EnMAP (Environmental Mapping and Analysis Program; www.enmap.org) is planned to be launched in 2019. It has a target lifetime of five years.

EnMAP is a German satellite mission with a Hyperspectral Imager (HSI) for measuring, deriving, and analyzing 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. The imaging spectrometer consists of two 2-dimensional detector arrays, one for Visible and Near InfraRed (VNIR) and one for ShortWave InfraRed (SWIR). Jointly with the German Space Operations Center the EOC is responsible for the establishment and operation of the EnMAP ground segment. EOC is contracted by DLR to build the operational processor for DLR. Table 1 gives an overview of EnMAP satellite, instrument, and processors (Storch et al., 2013).

Based on studies, since October 2008 EOC develops the operational processors for EnMAP data (Storch et al., 2008; Guanter et al., 2015). Since August 2010, the processors are in Phase D.

Due to the fact that acquisitions cover up to 1020 km × 30 km, the Level 0 processor divides them into 30 km × 30 km tiles in order to simplify the data handling also on end users' site. However, information relevant to or based on the complete acquisition, namely to achieve consistency between neighbouring tiles, are annotated to each Level 0 product, that are long-term archived. These are information on dark current measurements, which are performed before and after each acquisition, to ensure the high radiometric accuracy, geometric sensor model improvements based on image matching techniques to robustly improve the pointing knowledge from 100 m (absolute) to 30 m (relative), as well as water vapour and aerosol optical thickness maps for an accurate atmospheric correction. The Level 1B processor inputs are Level 0 product together with corresponding valid calibration tables as well as orbit and attitude products, whereas for the Level 1C and Level 2A processor the input is solely the output of the previous processor (Storch et al., 2009; Müller et al, 2009; Müller et al., 2010).

Table 1. EnMAP characteristics.

Mission	**EnMAP**
Target lifetime	2019-2024
Satellite (mass, dimension of main body)	1000 kg, 2.0 × 1.8 × 1.7 m^3
Orbit (type, inclination, hight, period, local time at equator)	Sun-synchronous, 97.96°, 653 km, 5856 s, 11:00
Instrument name	HSI (2 instruments)
Instrument type	hyperspectral: Visible and Near InfraRed, ShortWave InfraRed
Off-nadir pointing in across-track	≤ 30°
Revisit frequency	≤ 4 days (≤ 30° off-nadir), ≤ 21 days (≤ 5° off-nadir)
Spatial resolution	30 m
Swath	30 km
Spectral resolution	228 bands
Spectral range	420-2450 nm (continuous)
Radiometric resolution	14 bit
Processing levels	L0, L1B, L1C, L2A
DEM	Combination of SRTM C- and X-band data and GLOBE, but usage of TanDEM-X DEM under consideration
REF	Combination of EU37 REF based on SPOT and IRS-P6 data and Global REF based on Landsat data, but usage of Sentinel-2 data under consideration

OVERALL IMAGE PROCESSING CHAIN

In order to generate 3 different EnMAP products delivered to a user (+1 internal product) there are 4 processors (Fig. 1). The L0 product is always generated for long-term archiving in DIMS Product Library. The L1B, L1C and L2A products are generated by the processors called in different sequences and stored only temporarily on the pick-up points for delivery (De Miguel et al., 2010; Storch et al., 2011; Müller et al., 2012; Storch et al., 2017).

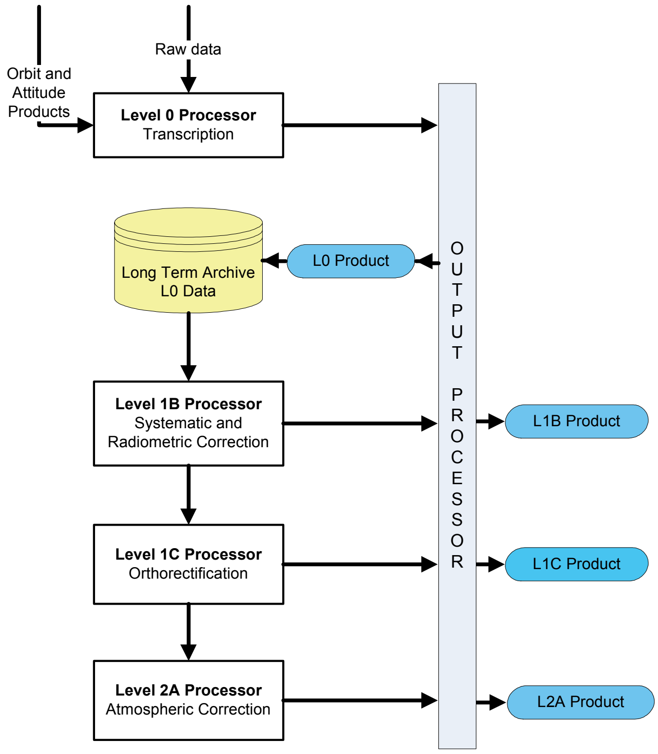

Figure 1. Processing chain for EnMAP HSI.

Level 0 Processing

The level 0 processor combined with quicklook generation as well as quality derivation generates an internal product (not available for the users). It mainly collects and pre-processes the information from the different data streams (Fig. 2).

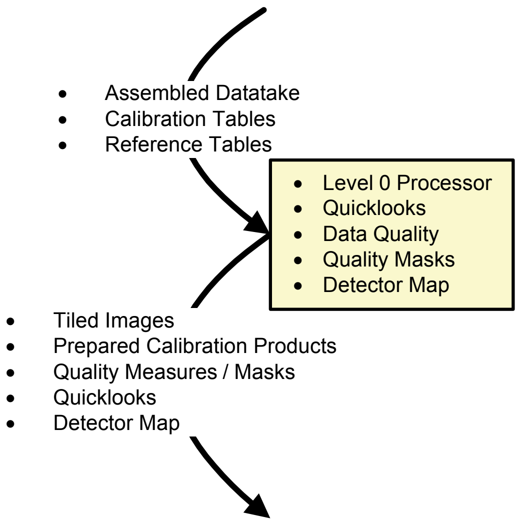

Figure 2. Processing chain for L0.

Level 0 Processing steps:

Transcription and screening

- General
  - The source packets for each channel file will be unpacked. This process includes the removal of packet headers, the interpretation of header information and the preparation files for further processing.
  - Unpacked channel files of the spectral image will be decompressed. Decompression will be performed for each file separately.
  - The screening of the data will check whether all status information, temperatures, currents and voltages are available in the virtual channel (VC) and whether they are in the working range.
  - Dark current (DC) measurements before and after datatake acquisition will be extracted for each sensor and channel file separately and reformatted (e.g. to band sequential format). A separate product for the ingestion in DIMS archive will be created.
- Earth Datatake
  - Datatake tiling will be performed after cutting off the DC measurements. Each image tile will have the size of 1024x1024 pixels (approximately 30x30 km²). Due to the time separation of about $\Delta t = 88$ msec between data collection of the VNIR and SWIR instrument the ground coverage collected by the VNIR instrument is shifted in flight direction of about 20 pixels w.r.t. the VNIR collected data according to about 600m on ground.
  - Quality masks and measures will be derived – namely abnormal pixels, cloud and haze mask, water-land information, detector map and other derived metadata.
- Calibration Datatake
  - Calibration measurements (e.g. full aperture sun diffuser, deep space, internal lamp or LED measurements) will be evaluated, interpreted and additional calibration information is derived.

Quicklooks

- For each sensor two quicklooks will be generated. One quicklook in sensor geometry, to be delivered with L1B products and an orthorectified quicklook, to be delivered with L1C and L2A products.
- The quicklook files of VNIR scene will be transformed to 8-bit pixel values and radiometrically adjusted for optimal displaying. For the VNIR quicklook generation the following channels will be used: 550nm (blue), 670nm (green), 850nm (red).
- The quicklook file of SWIR will be transformed to 8-bit pixel values and radiometrically adjusted for optimal displaying. For the SWIR quicklook generation the following channels will be used: SWIR: 1050nm (blue), 1650nm (green), 2200nm (red).

Quality assessment

- Dead/abnormal mask generation:
  - A common dead pixel mask (VNIR + SWIR) with a size of Njx(NchVNIR+NchSWIR) (Nchs - number of channels of maximal configuration for the corresponding sensor) will be generated. It will be used for marking of the dead pixels in the data (local dead pixel mask). A pixel will be marked as dead or abnormal if one of the following criteria will be fulfilled:
    - no response (cold pixel)
    - saturated, even with low radiance input (hot pixel)
    - non-changing output
    - changing output, while permanently changing output, even constant input (flickering pixel, illumination dependent)
  - These criteria will be checked within the calibration procedures and the dead pixel mask will be changed, if necessary.
- Screening of raw data
  - The screening results of the raw data will be written in the metadata file for quality assessments and further processing.
- Generation of other quality masks and parameters
  - Within a classification procedure haze/cirrus/shadow/snow/land/defects masks as well as a cloud cover index will be created. Similar to the quicklook files each mask will be generated in sensor geometry and orthorectified format.

Level 1B Processing

The L1B 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 Fig. 3.

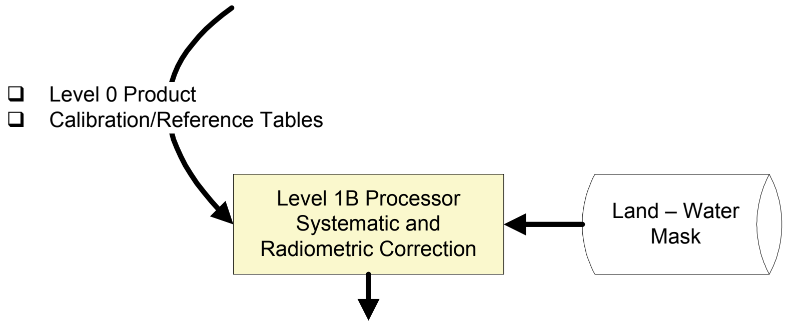

Figure 3. Processing chain for L1B.

Level 1B Processor Package

- Dead and abnormal pixels as well as saturated pixels will be flagged using information of radiometric calibration tables. In this process not only saturated pixels will be considered, also pixels saturated in a previous frame(s) or pixels that have saturated neighbouring pixels and thus could be effected by blooming will be taken into account.
- Non-linearity response will be corrected (spatial and spectral direction). For this LUT (look-up tables) for non-linearity correction will be used: DNlin = LUT(DN), where DN -- digital number.
- The offset for the SWIR spectrometer will be subtracted (for the VNIR spectrometer the electronic offset is already internally corrected)
- Dark current measured before and after each data take will be subtracted.
- For response non-uniformity (RNU) correction (spatial and spectral direction, flat fielding) look-up tables or polynomial will be used: DNcor = RNU*(DNlin – DNDS – DNstray), where DN – digital number.
- Stray-light correction (spectral and spatial direction, deconvolution) will be done by applying corresponding 2D matrices (for spatial and spectral cases) that contain weighting coefficients. The straylight contribution to a particular pixel will be removed by subtracting from the pixel's reading values of all other pixels multiplied by the weighting coefficients.
- Gain matching for VNIR detector (spectral direction) will be applied either during image processing from Level 0 to Level 1B Product where all low-gain readings have to be multiplied by corresponding gain matching coefficients to "match" the high gain trend or during normal image processing after completing gain matching where the evaluated DNs can be converted to radiance units by using high-gain radiometric coefficients only.
- Spectral referencing of each pixel to its spectral response function will be described by centre wavelength and FWHM (full width half maximum).
- Radiometric referencing will require the introduction of an absolute calibration gain. Each pixel will be referenced to the corresponding radiometric coefficient from the Radiometric Coefficient Table. The resulting Level 1B Data Product will be a hyperspectral cube (3D matrix) containing digital numbers corrected for systematic and radiometric errors and spectrally characterized and a 2D matrix with radiometric coefficients which have to be applied in order to convert the digital numbers into radiances.

Land/Water Mask

- Topographic information will automatically be transformed into satellite projection, in order to provide land-water-distribution congruently to remote sensing data for further processing. The topographic information of the CIA world map data base on a scale 1:100 000 is used for producing the land-water-mask.

Level 1C Processing

The EnMAP level 1C processor produces the geolayer required for orthrectification by applying the technique of Direct Georeferencing (DG). This physical method 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. Fig. 4. illustrates this part of the processing chain.

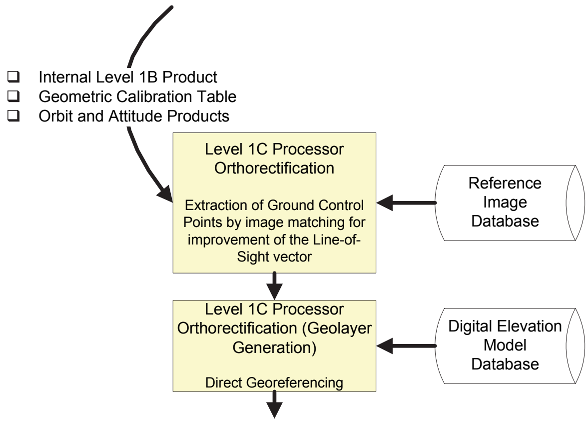

Figure 4. Processing chain for L1C.

<u>Level 1C Processing steps:</u>
Direct Georeferencing

- Direct Georeferencing (DG)
  - Attitude and position/velocity measurements will be synchronized with time tagged image lines using appropriated interpolation. The attitude auxiliary data (unit quaternions with 1 Hz repetition rate) will be first transformed to Euler angles and then calculated for each scan line using Spline or adaptive Chebyshev approximation with the fallback option of Lagrange interpolation. For position and velocity determination the scan lines will be synchronized with the elements of the exterior orientation. To this end the time information (GPS time) of each scan line of the downlinked data will be extracted from the virtual channel. For all datasets to be synchronized the seconds since beginning of the year serve as time base. The ephemeris auxiliary data will be calculated for each scan line using Lagrange interpolation.
  - Pixel view vectors (also called pixel Line-of-Sight LoS vector) will be established using the sensor internal geometry, payload assembly geometry and time dependant satellite motion during image acquisition. The sensor look direction vectors will be derived from laboratory and/or in flight geometric calibration.
  - The collinearity equation will be set up to relate locations of image pixels with an earth reference coordinate frame.
- DEM Intersection
  - The DEM will be projected to the coordinate frame specified in the DG model. For the EnMAP HSI the relation between an object point (real world coordinates) and the same object point measured by the pixel location and coordinated in the sensor coordinate frame.
  - The DEM will be interpolated to generate a dense grid of height values appropriate for the orthorectification task.
  - The DEM and LoS vector will be connected by an iterative procedure in order to retrieve object point coordinates for each image pixel. For this a model coordinate frame will be introduced realized by a local topocentric system (LTS). To this end the LoS vectors, the state vectors and the DEM will be transformed to a LTS with a fundamental point close to the scene centre (derived from the scene corner coordinates). The transformation of the DEM to the model coordinate frame includes a bilinear resampling with a pixel spacing of 30m (similar to the EnMAP HSI Ground Sampling Distance).

- Map Projection
  - A geodetic datum transformation database and map projection functionality will be provided.
  - The object points will be transformed to a map projection like global (e.g. UTM), continental (e.g. European LAEA ETRS89).
- RPC Generation
  - The Rational Polynomial Coefficients (RPC) are derived using the rigorous sensor model.
- Geolayer Generation
  - A geolayer will be generated for SWIR and VNIR each. This geolayer is used in the Output Processor to resample the output image.

Model Parameter Improvements

- Processing Chain for Orthorectification
  - The preparation of the processing chain will be based on the selection of a set of channels of the EnMAP VNIR image data cube in order to produce images which are suitable (e.g. radiometric similar for optical references, high contrast for DEM shaded references) for matching with the images in the reference database.
  - The DEM & reference tile generation process will select appropriate tiles from the DEM database and from the reference database and will mosaic them with a margin of about 1 km (2 x 500 m according to the EnMAP pointing accuracy of 500 m) due to the pointing knowledge of the sensor.
  - Coarse Orthorectification will be based on the four image corner coordinates and will perform a simple affine transformation. The coarse orthorectified images will serve as input for an automatic image matching with the reference image tiles and will be necessary as starting point for the hierarchical and shaded DEM matching algorithm.
  - Automatic tie point generation by matching will apply the methods of hierarchical intensity based matching and object based matching for optical data as shaded DEM matching for DEM in order to extract automatically GCP/ICP (Ground Control Points / Independent Control Points) from the reference data.
  - GCP/ICP Generation will transform the identified tie points back to the original image space and will classify the tie points to GCPs for an improvement of the orthorectification and to ICPs for quality assessments.
  - Model parameters will be estimated using the GCP information for an improvement of orthorectification parameters. Depending on method and reference data the GCP information will be weighted within the Least Squares Adjustment. Iterative blunder detection will be integrated, which eliminates step by step GCPs with a residual greater than a threshold of 2 pixels starting with the bottom quality GCP.
  - Orthorectification will be applied for EnMAP SWIR and VNIR tiles independently using the DG technique which automatically achieves co-registered images.
  - Quality assessment will derive geometric quality parameters like RMSE values and residual plots where ICPs will serve as input.
- Intensity based Image Matching
  - The matching process will use a resolution pyramid to cope with large images differences between the reference and the coarse registered image.
- Feature based Image Matching
  - As a fallback to the Intensity based Image Matching, a feature based approach using SIFT (Scale-invariant feature transform) can be used to match the reference and the coarse registered image.
- Optical Reference Image Databases
  - According defined requirements as sampling distance, geometric accuracy etc. global and regional reference images produced by optical satellites will be selected.
- Model parameter estimation
  - Using GCP a refinement of model parameters by iterative least squares adjustment will be performed in order to achieve an improvement of the geometric accuracy of the orthoimages.
  - Weight matrix determination will be taken into account for quality assessment in case different reference databases and/or image matching techniques have been applied in order to derive GCP.
  - Different levels of blunder detection will be included in the process chain to determine a set of GCP of high geometric quality.

Quality

- The geometric corrected product should have accuracy at nadir view < 100m (1 sigma, all 3 axes).
- The geolocation accuracy at nadir look direction of the level 1C products shall be better than 1 GSD (1 sigma) in each direction with respect to reference images provided suitable reference images are available.

Level 2A Processing

The EnMAP level 2A processing performs atmospheric corrections of the images employing separate algorithms for land and water applications. The atmospheric correction processor produces reflectance values for land and water areas and generates cloud masks. Fig. 5. illustrates this part of the processing chain.

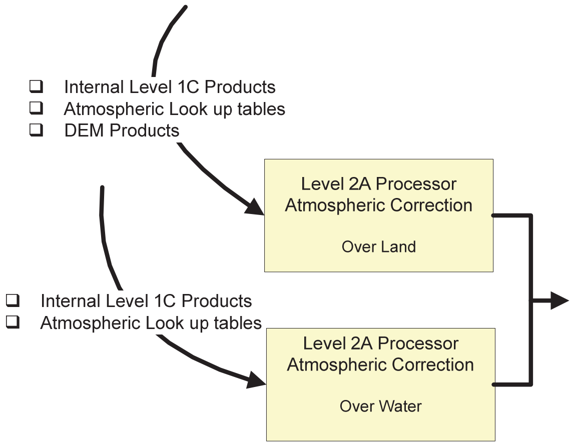

Figure 5. Processing chain for L2a.

<u>Level 2A Processing steps:</u>

Land Applications

- Masks for land, water, haze, cloud, shadow provided as output of the level 1B processor will be improved during atmospheric correction.
- Quality layers as cloud probability, water probability and snow probability will be calculated with spectral criteria.
- Radiative transfer calculations will be performed using the scaled DISORT with 8 streams for the atmospheric windows and the correlated k for the absorption regions.
- An atmospheric database will be needed for the resampling of the six atmospheric functions (path radiance, direct and diffuse transmittance ground-to-sensor, direct and diffuse solar flux and spherical albedo) with the channel filter curves. This database will be calculated using the original MODTRAN calculations and will be suitable for instruments ≥ 3 nm.
- Aerosol type and optical thickness will be determined after performing an automatic retrieval over land.
- Columnar water vapour will be calculated with the APDA algorithm using measurement channels around 0.94 µm / 1.13 µm and appropriate reference or window channels around 0.88 µm, 1.02 µm, and 1.08, 1.24 µm, respectively.
- The EnMAP image processing will be performed with the AC2020 code that accounts for flat and rugged terrain as well as the influence of ozone and includes haze/cirrus detection as well as removal algorithms.

Water Applications

- A sun glitter mask will be prepared by identification of specular reflection (“sun glint”) on water bodies. This mask will be stored for the scene if the probability of sun glint exceeds a defined threshold (Rgl int = 2%).
- For correction of the water mask new values will be generated using the algorithm described in the section “water pixel detection” and compared with the water mask from level 1B

- Cirrus detection and correction will be performed for all water pixels not covered with clouds and not affected by sun glitter.
- Adjacency correction.
- Retrieval of aerosol optical thickness.
- Atmospheric correction will be performed for all water pixels not covered with clouds and not affected by sun glint. Only the channels in the spectral region 400-900nm are processed.
- As radiative transfer databases monochromatic and sensor databases will be used.
- Quality assessment will be provided in percent for water pixels and clear water pixels in a scene as well as the mean value of retrieved aerosol optical thickness over water.

Output Processor

The output processor generates the product and the metadata for the requested product.

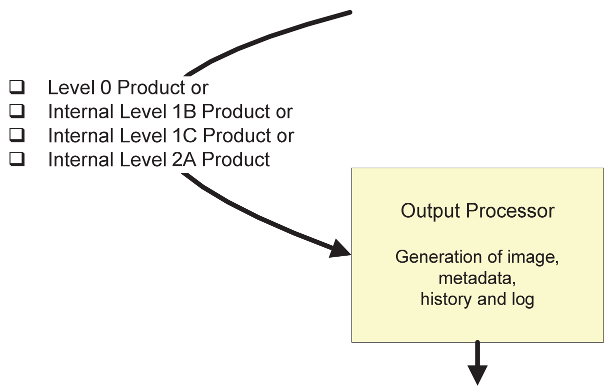

Figure 6. Output processor.

Output Processing steps:

- A spectral image will be produced based on the selected product format. For Level 0 products each tile will be archived in BSQ format. Here no selection is possible as the L0 product will not be delivered.
- Metadata will be produced as an xml file according to the defined structure in the product specifications.
- A history and log file as well as a detector map will be produced and archived in an appropriate device located in NZ. All 3 files will not be delivered. The logging mechanism generates a product report based on the output of each executed processor.
- Resampling: Different resampling techniques (Nearest Neighbour, Bi-linear, Cubic Convolution,) appropriate for output generation based on the geolayer produced by the L1C processor will be provided. The image resampling is based on transformed polygons (triangles) from the image space to the object space. The input image grid will be covered by a dense net of triangles which are mapped to the output image grid. The resulting triangles will be filled by interpolated pixel values using the different resampling methods.

Quality Control Activities

Quality Control Activities include both automated data QC procedures within the L1B, L1C and L2A processors as well as interactive data QC procedures for selected scenes (see Fig. 7).

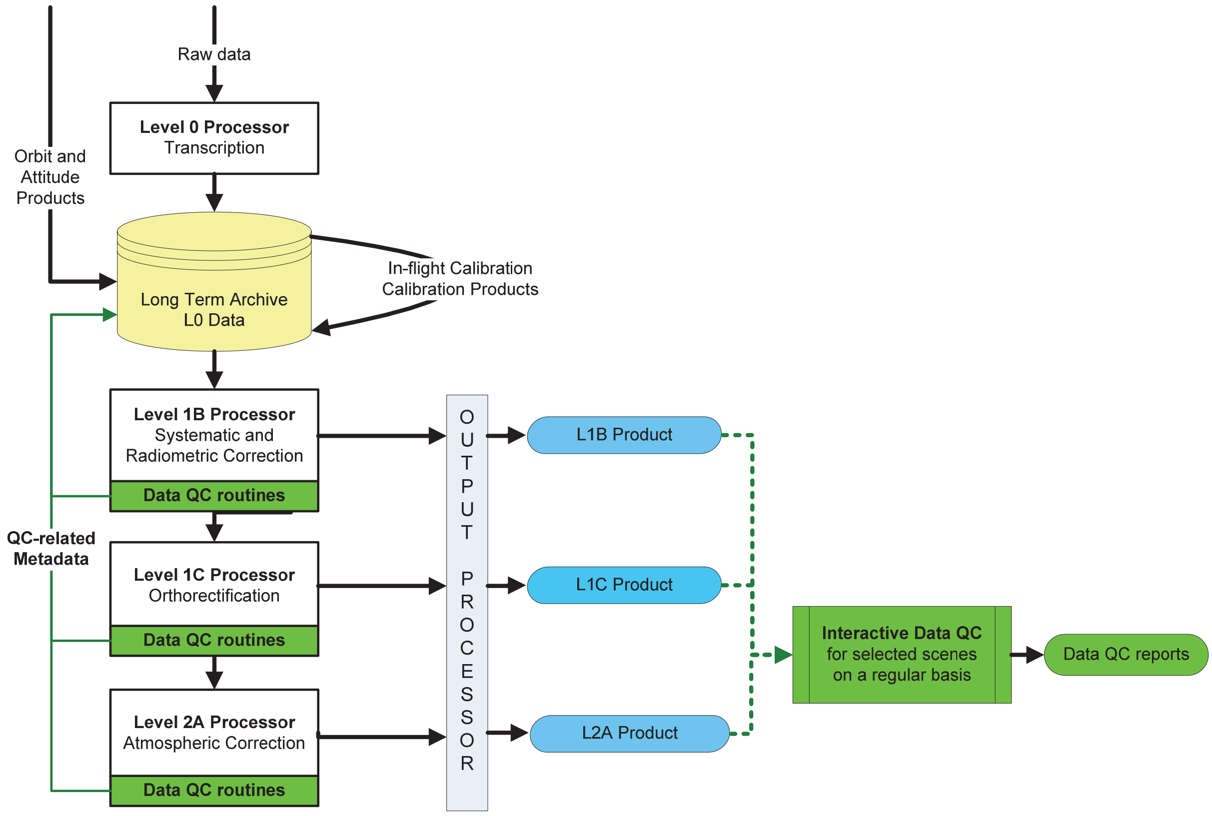

Figure 7. Scheme of the data workflow related to Data QC.

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 (Bachmann et al., 2016). 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 (Bachmann et al., 2017). On a regular basis an additional interactive QC analysis will be carried out. This is necessary since certain properties can not be analysed in a fully automated way.

CONCLUSION

The design of the EnMAP (Environmental Mapping and Analysis Program; www.enmap.org) ground segment and in particular of its hyperspectral image processing chain is presented. The status corresponds to the baseline for the production activities of the ground segment, namely only minor changes on the design are expected.

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