Processing Chain, Calibration and Data Quality Procedures of the Future Hyperspectral Satellite Mission EnMAP

DLR German Aerospace Centre
*M. Bachmann, C. Makasy, A. de Miguel, A. Müller, R. Müller, A. Neumann, G. Palubinskas, R. Richter, M. Schneider, T. Storch, T. Walzel*

GFZ Deutsches GeoForschungsZentrum
*H. Kaufmann, L. Guanter, K. Segl*

EOMAP GmbH&Co.KG
*T. Heege, V. Kiselev*
… but first a few words on airborne hyperspectral in Europe:
EUFAR – European Facility for Airborne Research

- Objective: **Trans-national access to research infrastructure**
- Total of 33 European institutions, 22 instrumented aircrafts
- All major PAFs for airborne hyperspectral data in Europe & Israel included
  - PML/NERC, INTA, DLR, VITO/RSL, USBE, TAU, FUB (ONERA associated)
  - Access to 6+ hyperspectral instruments
- Flight hours, instrument & processing costs covered by European Commission (FP7)

- **Joint Research Activities** – for Hyperspectral:
  - To develop **quality indicators and quality layers** for airborne hyperspectral imagery
    - Uncertainty propagation studies for pre-processing
    - Harmonization of data QIs
    - Recommendation on algorithms
  - In addition: **Standards & Protocols** (“best practice”) for airborne research

http://www.eufar.net
EnMAP (Environmental Mapping and Analysis Program) is a German hyperspectral satellite mission providing high quality hyperspectral image data on a timely and frequent basis. Main objective is to investigate a wide range of ecosystem parameters encompassing agriculture, forestry, soil and geological environments, coastal zones and inland waters.

OUTLINE

- EnMAP mission (Characteristics, Elements)
- Automatic and operational processors for product generation
- Mission status
Mission and Instrument Characteristics

### VNIR Detector Array
- Wavelength: $420 \text{ nm} < \lambda < 1000 \text{ nm}$
- Signal-to-Noise: $>500$ @ 495 nm
- Sampling: 6.5 nm
- Thermally controlled to 0.1 K
- FPA: Complementary Metal Oxide Semiconductor (CMOS)
- Total Length per Day: $> 5000 \text{ km}$
- Maximum Track Length: 1000 km
- Swath Width: 30 km
- Ground Pixel Size: 30 m $\times$ 30 m
- Operational Lifetime: $>5 \text{ years}$
- Orbit: 643 km @ 48°N (Sun-Synchronous)
- Local Crossing Time Descending Node: 11:00 hrs 15 min
- Inclination: 97.96°
- Orbit Period: $\sim 98 \text{ minutes}$

### SWIR Detector Array
- Wavelength: $900 \text{ nm} < \lambda < 2450 \text{ nm}$
- Signal-to-Noise: $>150$ @ 2200 nm
- Sampling: 10 nm
- Actively cooled: 150 K
- FPA: Mercury Cadmium Telluride
- Pointing Capability: 30 (± 5)
- Target Revisit Time: 4 days (23 days)
- Dynamic range: 14 bit
- X-Band Downlink: 320 Mbps
- Spectral Range: 94
- Orbit Period: $\sim 98 \text{ minutes}$

### EnMAP Satellite
- Operational Lifetime: $>5 \text{ years}$

### Orbit Information
- Orbit: 643 km @ 48°N (Sun-Synchronous)
- Local Crossing Time Descending Node: 11:00 hrs 15 min
- Inclination: 97.96°
- Orbit Period: $\sim 98 \text{ minutes}$

### Swath Width Information
- Swath Width: 30 km
- Ground Pixel Size: 30 m $\times$ 30 m
- Optical pointing range: 30 (± 5)
Overview Processing Chain

Level 0 Processor
The transcription processor de-compresses and collects information from different data streams, extracts and interprets information, performs screening, generates image tiles, adds data quality information.

Level 1 Processor
The systematic/radiometric correction processor converts raw image pixels values to at-sensor radiance physical values.

Level 2geo Processor
The geometric correction processor orthorectifies images using different methods (with and without automatically extracted GCPs).

Level 2atm Processor
The atmospheric correction processor produces reflectance values for land and water areas and generates cloud masks.

Output Processor
The output processor generates the product, the metadata and derives the log information from the information produced by the logging service.
Overview Processing Chain

Ensuring data quality:
• **Automated** within processors
• **Interactive** procedures
• **Independent** validation

1. **Level 0 Processor**
   - Transcription
   - Orbit and Attitude Products
   - Long Term Archive L0 Data

2. **Level 1 Processor**
   - Systematic and Radiometric Correction
   - Data QC routines

3. **Level 2geo Processor**
   - Orthorectification
   - Data QC routines
   - L1 Product

4. **Level 2atm Processor**
   - Atmospheric Correction
   - Data QC routines
   - L2atm Product
   - L2 Product

Output:
- Interactive Data QC for selected scenes on a regular basis
  - Data QC reports
- Independent Validation for selected ground reference sites
  - Validation reports
EnMAP Level 1 Processing

Performs:
- Systematic Correction
- Radiometric Correction

Creates:
- At-sensor radiance
- Metadata for further processing

Example: ALOS Processor on behalf of ESA
EnMAP Level 1 Processing – detailed steps

- Bad (dead & suspicious) pixel flagging
- Non-linearity correction
- Dark signal correction
- RNU correction
- Gain Matching (VNIR)
- Spectral referencing
- Spectral straylight correction
- Spatial straylight correction
- Radiometric referencing
EnMAP Level 2geo Processing

**Performs**
Geometric image corrections realized by different process flows

**Creates**
Orthoimages
Acc. < 3 GSD without Ref.
< 1 GSD with Ref.

**Selectable Parameters**
Projection:
UTM (Zone of center) (± 1 zone)
Geographic

Resampling:
Bi-cubic
Bi-linear
Nearest Neighbour

Example: ALOS Processor on behalf of ESA
EnMAP Level 2geo Processing using Reference Scenes

Original image → Matching → Tie points GCP / ICP → Improvement of Line-of-Sight Vectors → Generation of ortho image → Ortho image

Global reference image database → Reference image

Global DEM database → DEM

Metadata
- state vectors
- attitude
- sensor model
- time sync
- ...

Quality parameters derived from ICPs
EnMAP Level 2geo Processing with automatic GCP extraction – heritage

European Mosaick (~3700 Scenes)
- IRS-P6 LISS III
- SPOT 4 HRVIR
- SPOT 5 HRG

Overall mean accuracy w.r.t. reference data set (~450 ICPs per 1000 km²)
\[ \text{RMSE}_{x/y} \sim 10 \text{ m} \quad (\text{CE64} \sim 14\text{m}) \]
EnMAP Level 2atm Processing

**Performs**
Atmospheric Correction
over land and water
Haze / Cirrus Removal
based on
   ATCOR (Land)
   MIP (Water)

**Creates**
Surface Reflectance
haze/cloud/water/land mask

**Selectable Parameters**
Only land / water
Combined product (if appl.)
Haze / cirrus removal
Flat / rugged terrain
Water type (clear / turbid)
…

Example: ALOS Processor on behalf of ESA
Level 2atm Land Surface Processing

Level 1: TOA radiance

- Land/water mask
- Cloud/ haze/ snow cloud shadow/cirrus
- Aerosol retrieval
- Water vapor retrieval
- Terrain correction, DEM, slope, aspect, skyview
- Adjacency correction
- Surface reflectance retrieval
- Land surface reflectance

Quality Indicators

- Quality flags
- AOT
- WV
- ρ

ATCOR databases

DDV, water

APDA

DEM

Quality flags
Level 2atm Water Surface Processing

Leve1: TOA radiance

- Water mask
- Sunglitter probability
- Shore region albedo retrieval
- Adjacency correction
- Aerosol retrieval
- Underwater reflectance retrieval
- Water subsurface reflectance

Water mask
Sunglitter probability
Albedo map
AOT map
MIP databases

- Water mask
- Sunglitter probability
- Shore region albedo retrieval
- Adjacency correction
- Aerosol retrieval
- Underwater reflectance retrieval
- Water subsurface reflectance
ATCOR: Example of Cloud Shadow Removal

HyMap scene, Chinchon, Spain, 12 July 2003, RGB=878, 646, 462 nm

Ref: Richter & Mueller, 2005
ATCOR: Example of Cirrus Removal

AVIRIS scene, Bowie MD, 7 July 1996, RGB=634, 547, 458 nm

Ref: Gao et al., 2002
EnMAP Level 2atm Processing
flat terrain vs. rugged terrain atm. correction

Radiation components flat terrain

\[ L = c_0 + c_1 \Delta N \]

\[ \rho = \frac{\pi (L - L_1)}{\tau (E_{\text{dir}} \cos \theta_s + E_{\text{dif}})} \]

Radiation components rugged terrain

\[ L_1 \]

\[ L_2 \]

\[ L_3 \]

Path

Pixel

Refl. Terrain Radiation

Adjacency Radiation

Surface reflectance
EnMAP Level 2atm Processing
high geometric accuracy necessary for topo correction

illumination map $\cos(\text{local SZA})$

atm + topo corrected
Geom. Acc. $< 1$ pixel

atm + topo corrected
3 pixel shift $\rightarrow$
<table>
<thead>
<tr>
<th>QC Entry</th>
<th>Parameter</th>
<th>Category</th>
<th>Report format</th>
<th>Metadata (DIMS IIF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>overallQuality</td>
<td><strong>Overall data quality</strong></td>
<td>all</td>
<td>R</td>
<td>Y Y</td>
</tr>
<tr>
<td>processorLog</td>
<td>Warning messages in processor log</td>
<td>IMG</td>
<td>R</td>
<td>Y</td>
</tr>
<tr>
<td>sceneSZA</td>
<td><strong>Solar zenith angle</strong></td>
<td>IMG</td>
<td>R</td>
<td>Y Y</td>
</tr>
<tr>
<td>sceneSunglint</td>
<td>Sun glint / sun glitter probability</td>
<td>IMG</td>
<td>R</td>
<td>Y</td>
</tr>
<tr>
<td>cloudCover</td>
<td><strong>Percentage clouds</strong></td>
<td>ATM</td>
<td>R, L</td>
<td>Y Y</td>
</tr>
<tr>
<td>hazeCover</td>
<td>Percentage haze</td>
<td>ATM</td>
<td>R, L</td>
<td>Y Y</td>
</tr>
<tr>
<td>cirrusCover</td>
<td>Percentage cirrus</td>
<td>ATM</td>
<td>R, L</td>
<td>Y Y</td>
</tr>
<tr>
<td>cloudShadow</td>
<td>Percentage cloud shadow</td>
<td>ATM</td>
<td>R, L</td>
<td>Y Y</td>
</tr>
<tr>
<td>sceneWV</td>
<td><strong>Average scene WV</strong></td>
<td>ATM</td>
<td>R</td>
<td>Y Y</td>
</tr>
<tr>
<td>sceneVIS</td>
<td>Average scene visibility / AOT</td>
<td>ATM</td>
<td>R</td>
<td>Y Y</td>
</tr>
<tr>
<td>sceneAtmParam</td>
<td><strong>Validity of atm. correction</strong></td>
<td>ATM</td>
<td>R</td>
<td>Y</td>
</tr>
<tr>
<td>sceneTerrain</td>
<td>DEM artifacts in terrain correction</td>
<td>ATM</td>
<td>R, L</td>
<td></td>
</tr>
<tr>
<td>internalMasking</td>
<td><strong>Masks</strong> generated during processing (cloud, shadow, haze, land / water)</td>
<td>ATM</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>specCal</td>
<td>Artifacts related to spectral calibration / ATCOR LUTs</td>
<td>SPEC, ATM</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

Blue: implemented in L2_atm land / L2_atm water processor
Mission Status

2003: Call for Proposals for a future Earth observation mission by DLR Agency
2004: EnMAP selected for Phase A study
2005: Phase A: study accomplished successfully (SRR)
2006: EnMAP selected for Phase B study
2007: Phase B: study accomplished successfully (PDR)
2008-2010: Phase C: Detailed Design (GS CDR passed in July ‘10) ✔
2010-2013: Phase D: Production, Test, Verification, Validation (ORR)
2014: EnMAP Launch with PSLV (LEOP & Commissioning Phase)
2014-2019: Operations Execution
2019- : De-orbiting
Thanks for your attention

www.enmap.org
Backup Slides ...
On-Board Calibration Means

Technical tools and operational modes to perform the necessary measurements for on-orbit calibration (and monitoring of instrument properties) throughout the mission:

- Shutter/calibration mechanism for dark value and calibration measurements
- Full aperture diffuser for Sun calibration (radiometric, absolute)
- Main integrating sphere (white Spectralon®) for relative radiometric assessment
- Secondary sphere (doped Spectralon®) for spectral calibration assessment
- Focal plane LEDs for linearity measurements

HSI in-flight calibration means except focal plane LEDs

(drawing © Kayser-Threde)
# Calibration measurements

## Summary of calibration measurements

<table>
<thead>
<tr>
<th>Calibration type</th>
<th>Time</th>
<th>Frames</th>
<th>Data Volume</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark (shutter)</td>
<td>23 sec</td>
<td>2 * 128</td>
<td>0.27 GB</td>
<td>each datatake</td>
</tr>
<tr>
<td>Dark (deep space)</td>
<td>30 sec</td>
<td>1 * 1024</td>
<td>1.38 GB</td>
<td>every 3 months</td>
</tr>
<tr>
<td>Relative radiance calibration</td>
<td>17 min 13 sec</td>
<td>1 * 512 (5steps)</td>
<td>1.66 GB</td>
<td>weekly</td>
</tr>
<tr>
<td>Sun calibration</td>
<td>140 sec</td>
<td>2 * 1024</td>
<td>1.38 GB</td>
<td>monthly</td>
</tr>
<tr>
<td>Spectral calibration</td>
<td>5 min13 sec</td>
<td>1 * 1024</td>
<td>0.83 GB</td>
<td>monthly</td>
</tr>
<tr>
<td>Linearity measurement</td>
<td>&lt; 5 min</td>
<td>2 * 128 * 40</td>
<td>5.8 GB</td>
<td>monthly</td>
</tr>
</tbody>
</table>
Data Quality Control

Including Quality Indicators (QI) for

General sensor characterization
  (e.g., spectral smile)

Sensor calibration issues
  (e.g., striping in pushbroom sensors)

Sensor performance during data acquisition
  (e.g., data drops)

External conditions during overflight
  (e.g., cloud coverage)

Processing
  (e.g., uncertainty of geo-location)

Quality of auxiliary data used in processing
  (e.g., DEM accuracy)
Addressing data QC related to radiometry

**Tasks:** assessment of **Data Properties** related to radiometry (**QC flag, QC report**), indication to trigger on-board calibration (S-320) and instrument monitoring (S-340)

**Issues:** incorrect or instable radiometric calibration (gain & offset values), contamination of detector elements

**Approach** for **automated** Data QC within L1 processor:
- Tests for scene / scene subset homogeneity
- Comparison with nominal values for:
  - Difference in column mean DN / mean radiance and STDEV (=> **striping**)
  - Correlation of neighboring bands within one column (=> **single detector failures**)
  - Overall band-to-band correlation matrix (=> **stability of radiometric calibration**)

- Striping in Pushbroom sensor data (MNF-transformed)
- Band correlation matrix (no band defects)
- Band correlation matrix (known de-calibration issues)
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<tr>
<td>stripingBanding</td>
<td>Artifacts related to radiometric calibration</td>
<td>RAD</td>
<td>R</td>
<td>Internal, Public</td>
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<tr>
<td>dualGain</td>
<td>Artifacts related to dual gain</td>
<td>RAD</td>
<td>R, L</td>
<td>Internal, Public</td>
</tr>
<tr>
<td>saturationCrosstalk</td>
<td>Saturation, cross-talk, blooming</td>
<td>IMG</td>
<td>R, L</td>
<td>Internal, Public</td>
</tr>
<tr>
<td>generalArtifacts</td>
<td>Other artifacts / suspicious pixel</td>
<td>IMG</td>
<td>R, L</td>
<td>Internal, Public</td>
</tr>
<tr>
<td>sensorLog</td>
<td>Warning messages related to sensor</td>
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<td>Artifacts related to spectral calibration</td>
<td>SPEC</td>
<td>R</td>
<td>Internal</td>
</tr>
<tr>
<td>signalToNoise</td>
<td>Signal-to-noise estimate</td>
<td>IMG</td>
<td>R</td>
<td>Internal</td>
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Blue: implemented in L1 processor
EnMAP Data QC for L2_geo products

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<tr>
<td>orthoTerrain</td>
<td>DEM-related displacements</td>
<td>GEO</td>
<td>R</td>
<td>Y</td>
</tr>
<tr>
<td>orthoRMSE</td>
<td><strong>Geometric accuracy</strong> of the orthoimage (I)</td>
<td>GEO</td>
<td>R</td>
<td>Y       Y</td>
</tr>
<tr>
<td>orthoResidual</td>
<td>Geometric accuracy of the orthoimage (II)</td>
<td>GEO</td>
<td>R</td>
<td>Y</td>
</tr>
</tbody>
</table>

Blue: implemented in L2_geo processor
Mission parameter

Sun-synchronous, 11:00 LTDN LEO – reference altitude 653km
3 axis stabilized platform with OCS
mass 850 kg / power 550 W avg.
512 Gbit mass memory / 320 Mbit/s X-band science data downlink
4 day global accessibility (30 off-nadir)
4 day target revisit capability
up to 50 data takes per day / total length 5000km
Sensor Parameter

Pushbroom type hyper spectral imager
Wavelength 420 - 2450 nm
30m GSD, 30 km swath (nadir)
228 spectral bands
VNIR 6.5 nm sampling
SWIR 10 nm sampling
SNR > 150 @ 2200nm (ref. radiance)
Polarization sensitivity < 5%
Smile and Keystone < 0.2 pix
Pointing knowledge 100m
Radiometric accuracy 5%
Radiometric stability 2.5%
Response Linearity 0.5%
Spectral accuracy 0.5nm / 1nm
Satellite Design

- Total Weight: ca. 850 kg
- Aver. Power: 450 W
- 512 Gbit mass memory
- 3 axis stabilized platform
- Pointing Stability: 1.5 m / 4 ms
- Pointing Knowledge: 100 m
  - 30 off nadir pointing for observation
- Hydrazine propulsion system for orbit maintenance & disposal
- 320 Mbit/s X-Band science data downlink
- Lifetime in Orbit: > 5 years
Instrument Optic Unit Design

Polished NiP coated Aluminum mirrors
Monolithic Aluminum structure
Quasi-isostatic mounting to platform
Starcameras attached to IOU for pointing knowledge
Redundant SWIR FPA due to cryocooler without flight heritage
Gravity release < 5μm – opt. elements
Eigenfreq. > 100 Hz
Active thermal stabilization to 21 C ± 1K
Instrument Optic Design

175mm EPD
F3 - unobscured

Novel spectrometer design
Dual, field separated spectrometer concept
good imaging performance
On-Board Calibration

Radiometric stability check: “integrating sphere with sources at different levels”
Sources: 10W Halogen lamps
white high power LEDs
Coupling to spectrometers via imaging optics
Different levels by driving varying currents

FAD?
Mission Elements

**EnMAP Space Segment**
- Satellite Bus (OHB Technology AG)
- Hyperspectral Imager (Kayser-Threde GmbH)

**EnMAP Ground Segment**
- MOS Mission Operation Center
  - Mission planning
  - Mission control
  - Flight dynamics
- PGS Payload Ground Segment
  - Instrument Planning
  - HSI Operational Processors
  - Data Storage & Delivery
- PCV Processor and Cal/Val
  - On-Board Spectral/ Radiometric Calibr.
  - HSI Development Processors
  - Validation/Ground Calibration
  - Instrument Monitoring

Orders → Data Products
- Internal, Charter, Cat 1 & 2, background mission users