Lessons learned from EnMAP in-orbit calibration and product harmonization for upcoming space-based hyperspectral missions

Miguel Pato[1,*], **David Marshall Ingram**[1], **Emiliano Carmona**[1]
EnMAP Ground Segment / PCV Team

3rd Workshop on International Cooperation in Spaceborne Imaging Spectroscopy
Noordwijk, 14.11.2024

[1] *German Aerospace Center (DLR), Remote Sensing Technology Institute, Oberpfaffenhofen, Germany*
* Miguel.FigueiredoVazPato@dlr.de

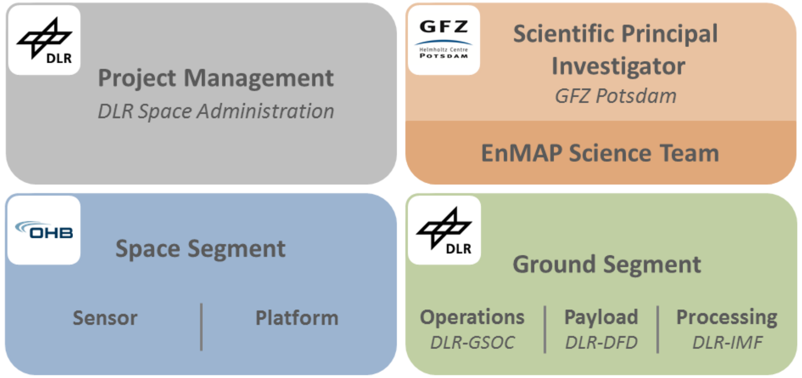
EnMAP Ground Segment / PCV Team: Martin Bachmann, Raquel de los Reyes, Tobias Eckert, Birgit Gerasch, Martin Habermeyer, Stefanie Holzwarth, Maximilian Langheinrich, David Marshall, Miguel Pato, Mathias Schneider, Peter Schwind and Helge Witt

Federal Ministry for Economic Affairs and Climate Action

EnMAP mission: requirements and fact sheet

https://www.enmap.org/

EnMAP specification	VNIR	SWIR
Spectral range	420 – 1000 nm	900 – 2445 nm
Number of spectral bands	91	133
Spectral sampling distance	6.5 nm	10 nm
Spectral full width at half maximum	6 – 11 nm	7 – 11 nm
Spectral accuracy	0.5 nm	1 nm
Spectral smile	<0.2 pix	
Signal-to-noise ratio	>500 (at 495 nm)	>150 (at 2200 nm)
Radiometric accuracy	<5%	
Radiometric stability	<2.5%	
Geometric accuracy	1 pix (30 m) with GCPs, otherwise 100 m	
VNIR/SWIR co-registration	0.2 pix	
L2A AOT, WV, BOA (land, water)	see Storch et al 2023	
Orbit type, altitude and inclination	Sun-synchronous, 653 km, 97.96°	
Orbit period and repeat cycle	1.6 h, 398 revolutions in 27 days	
Local time descending node	11:00 h ± 18 min	
Revisit time	4 days (±30° off-nadir tilt) 21 days (±5° off-nadir tilt)	
Ground sampling distance	30 m (at nadir; sea level)	
Swath width	30 km (2.63° across track)	
Swath length	1000 km / orbit; 5000 km / day	
Product size	30 km x 30 km	



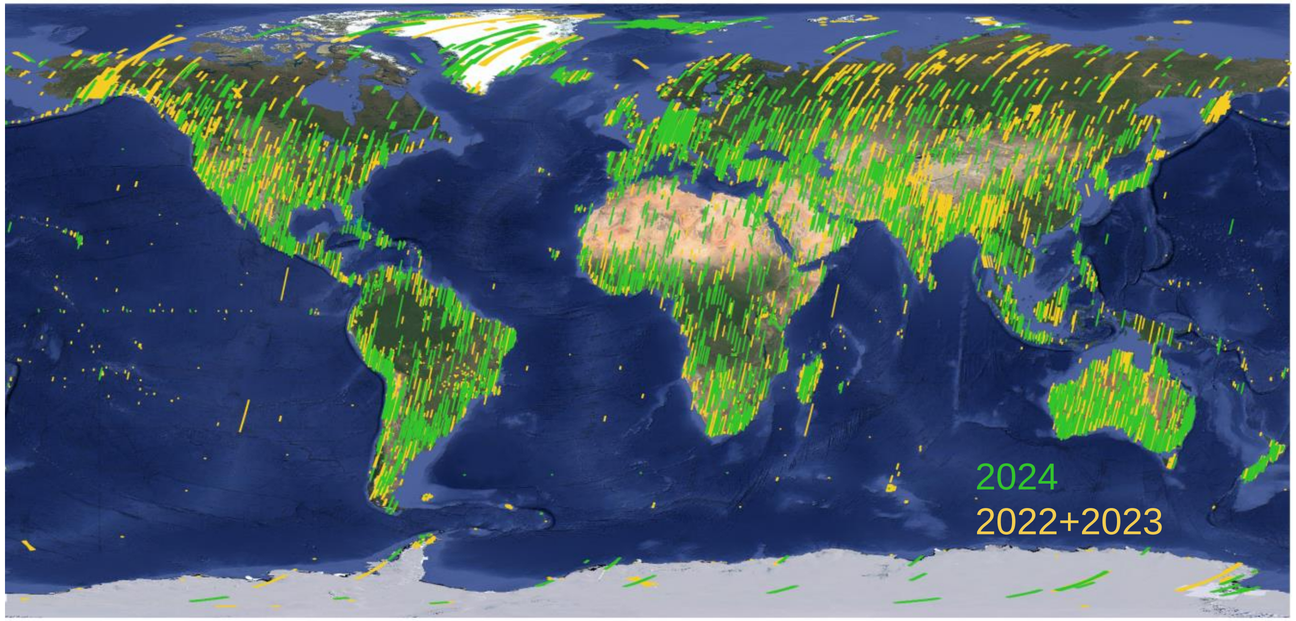
In-orbit calibration type	Mechanism	Frequency
Relative radiometric (lamp)	white spectralon	1x / week
Absolute radiometric (Sun)	Sun diffuser	1x / 2 months
Spectral	doped spectralon	1x / fortnight
Linearity	focal plane LEDs	1x / month
Deep space	dark sky	1x / month
Dark frames	closed shutter	before/after imaging

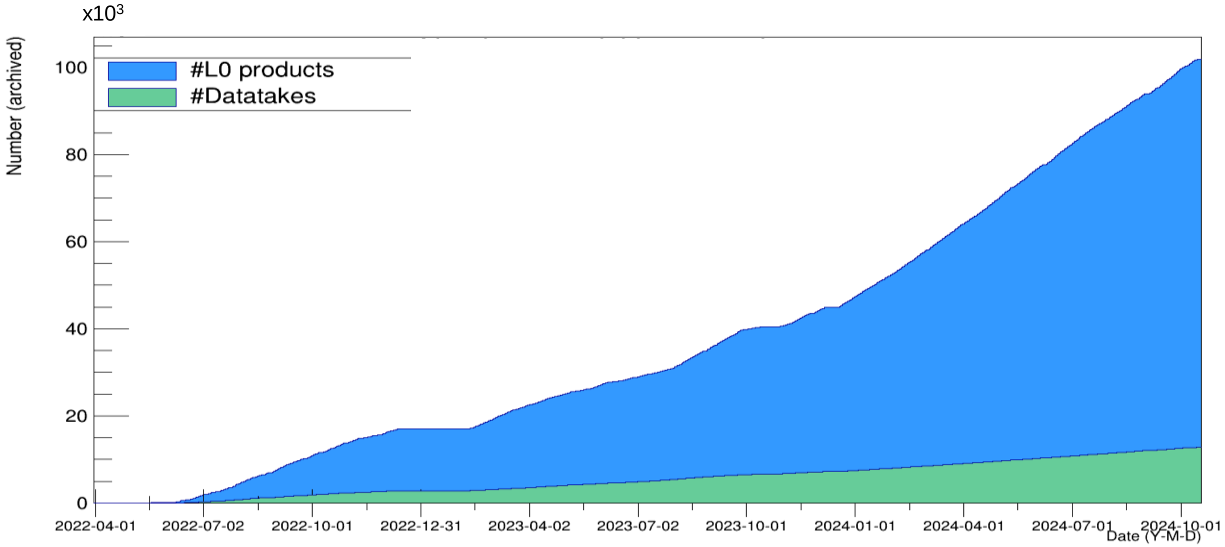
EnMAP mission: status of operations

Launch: 01.04.2022, Ops: since 02.11.2022

Status:

- All systems nominal, instruments in good health
- ~13 k Earth datatakes, ~102 k L0 products
- 240 calibration datatakes, 5 Moon datatakes
- Completed 2nd In-Orbit Operations Review and Mission Status Review in Oct 2024

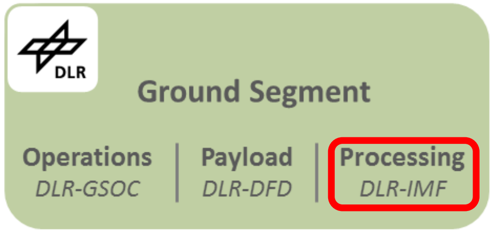




Elsewhere in this workshop:

- Mission status see talk by Laura La Porta (Wed 10:50)
- Foreground mission see poster by Nicole Pinnel (Wed 12:00)
- Product validation see talk by Maximilian Brell (Thu 11:20)
- Open science see talk by Sabine Chabrillat (Thu 12:00)

EnMAP processing and calibration



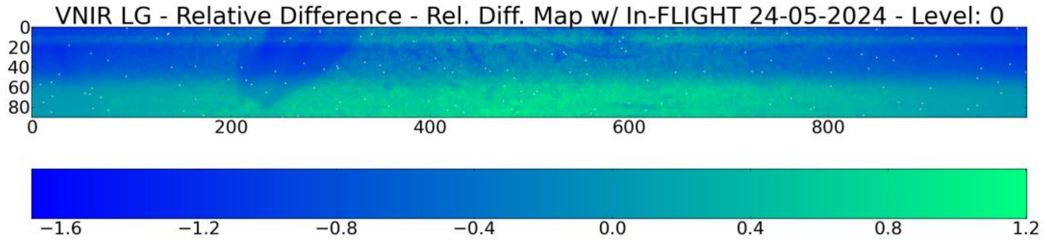
- In-flight calibration to update calibration tables
- Complex processing chain under continuous improvement to generate EnMAP products:
  - L0: raw data (internal only)
  - L1B: top-of-atmosphere radiances
  - L1C: orthorectified top-of-atmosphere radiances
  - L2A: orthorectified bottom-of-atmosphere reflectances (L2A land and L2A water)
- User products annotated with quality control and instrument monitoring information

Selected highlights: see processor change log: https://www.enmap.org/data/doc/EnMAP_processor_changelog.pdf

- Calibration: spectral and radiometric performance
- Processing and data quality: radiometry, geometry, atmospheric correction
- Instrument monitoring: Sun diffuser exposure

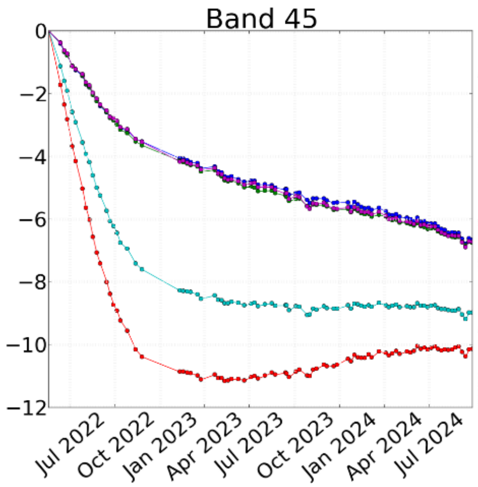
Spectral and radiometric performance

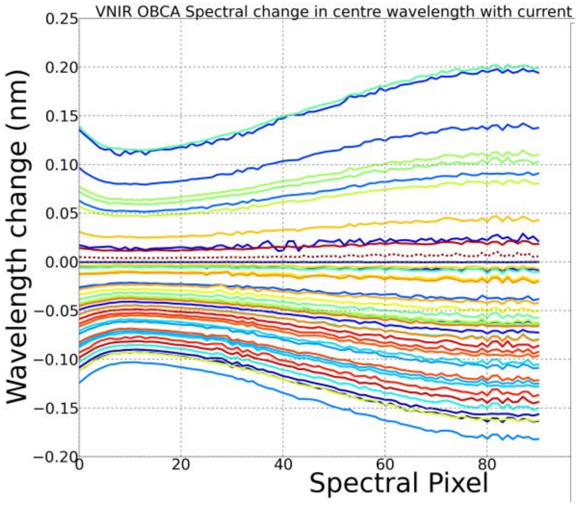
Highlight: Continuous monitoring of sensor performance with regular in-orbit calibration



Actions / results:

- Fast VNIR sensor degradation during first year slowed down by Mar 2023 but with differences across focal plane
- SWIR sensor very stable since launch
- Good spectral stability (<0.5 nm) for both VNIR and SWIR, last spectral update from Feb 2023
- Dark signal remarkably stable since launch
- VNIR/SWIR mismatch in overlapping spectral region under investigation



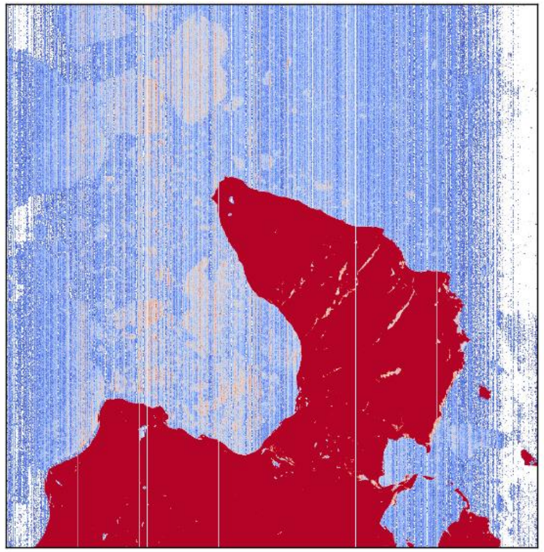


SWIR dark signal effect

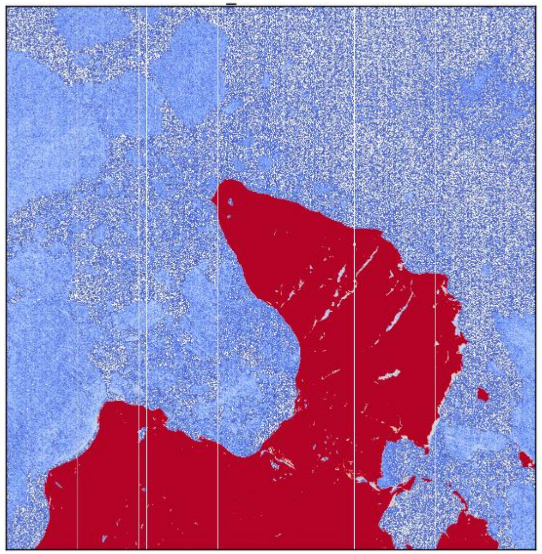
Highlight: L1B correction of unsubtracted SWIR dark signal fixing part of striping and small overcorrection

Actions / results:

- SWIR DC (LG/HG) not representative of SWIR dark signal in mixed gain used in imaging part for Earth datatakes
- Detailed discussions with Space Segment (OHB) and analysis of selected low-radiance scenes
- L1B correction based on night scenes feasible and effective
- Update will be available to users still in 2024 (likely in Nov)



before



after

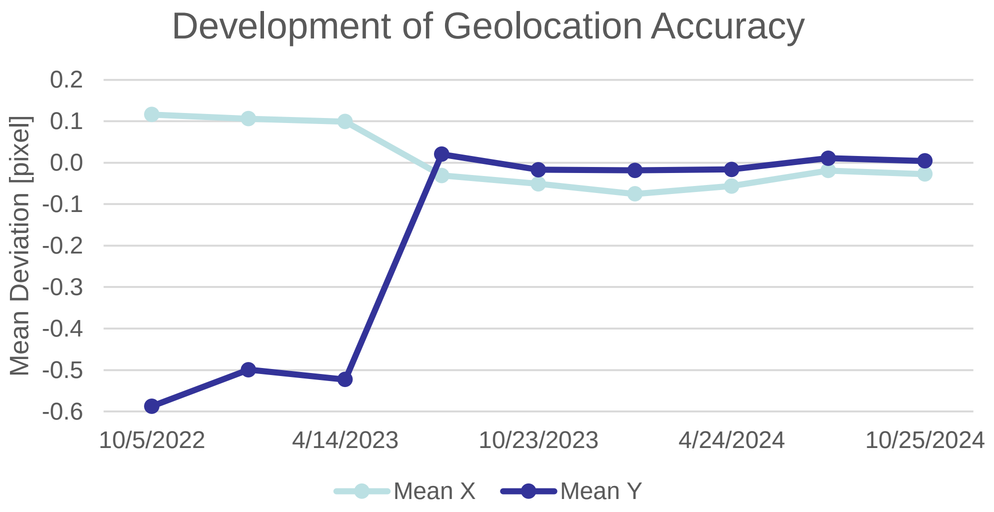
[Mission Quarterly Report #09, in preparation]

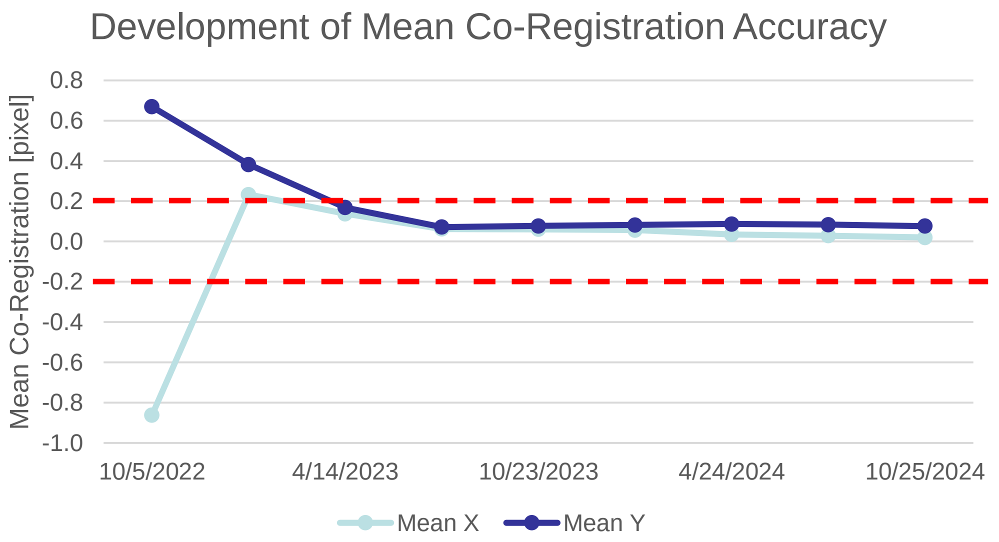
Geometrical performance

Highlight: Remarkable improvement of initially sub-optimal geolocation and co-registration errors

Actions / results:

- Detailed analysis led to fix of attitude processing (Aug 2022)
- Boresight calibration (Sep 2022) and geometric calibrations (Nov 2022, Feb 2023) performed
- Bug fixes in processor versions V01.02.00 (Mar 2023) and V01.03.01 (May 2023)
- Excellent geometrical performance since May 2023:
  - Geolocation: RMSE ~ 0.4–0.5 px (req: 1 px)
  - Co-registration: RMSE ~ 0.1 px (req: 0.2 px)
- Reprocessing of past L0 products ongoing, users should make sure that „archivedVersion“ >= V01.03.01

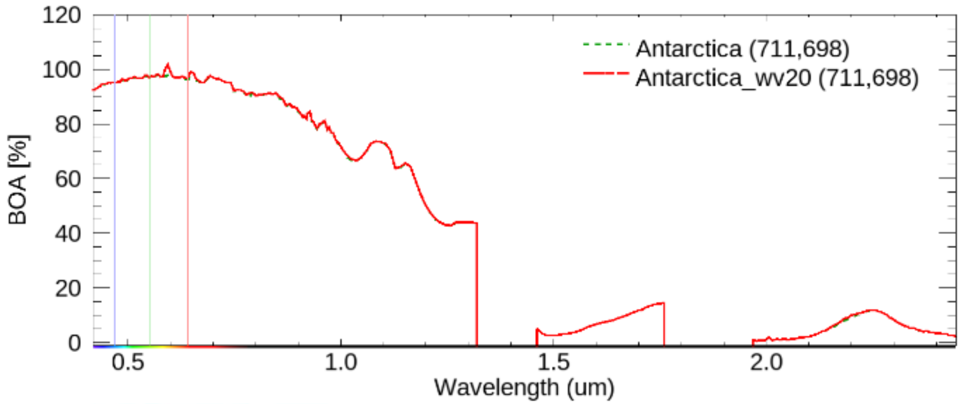


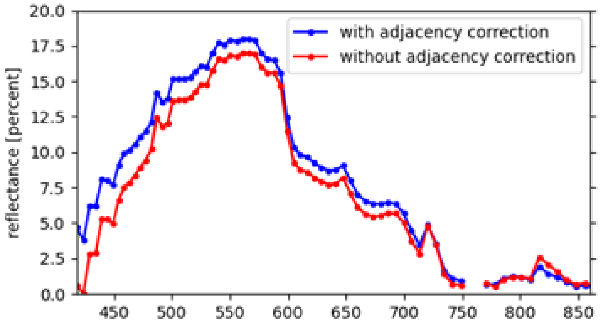


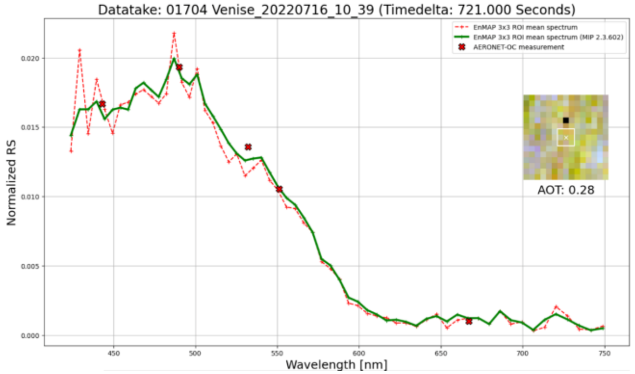
[Mission Quarterly Report #09, in preparation]

Atmospheric correction

Highlight: Fixing of small inconsistencies in L2A products reported by users







Actions / results:

- Fixed high reflectance in blue (processor version V01.03.03, Jul 2023) and features at 590 nm and 647 nm (V01.04.01, Dec 2023) in snow spectra
- Re-activated adjacency correction (V01.04.00, Sep 2023) and fixed spectral noise below 500 nm (V01.04.02, Mar 2024) in water spectra
- Fixing of adjacency correction artifacts and reflectance differences between tiles in land spectra in progress
- Users may simply re-order their products to benefit from improvements

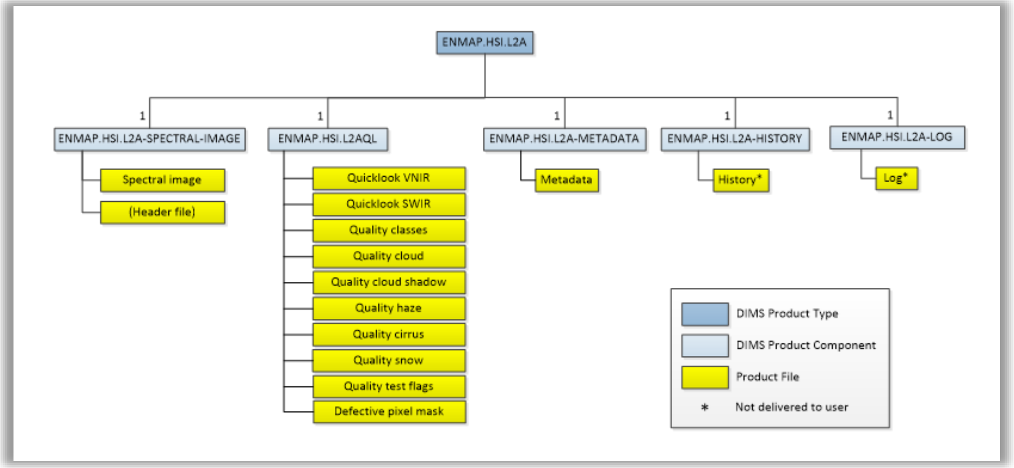
[Mission Quarterly Report #04, internal results]

Atmospheric correction

Highlight: Fixing of small inconsistencies in L2A products reported by users

Actions / results:

- L2A land product fulfills CEOS Analysis Ready Data CARD4L compliant requirements at threshold level
- QC-related metadata and flags generated L0 level and updated at LX level



	Threshold	Target
1. General Metadata		
1.1 Traceability	n.a.	no
1.2 Metadata Machine Readability	ok	ok
1.3 Data Collection Time	ok	no
1.4 Geographical Area	ok	ok
1.5 Coordinate Reference System	ok	ok
1.6 Map Projection	ok	ok
1.7 Geometric Correction Methods	n.a.	ok
1.8 Geometric Accuracy of the Data	n.a.	ok
1.9 Instrument	ok	ok
1.10 Spectral Bands	ok	ok
1.11 Sensor Calibration	n.a.	no
1.12 Radiometric Accuracy	n.a.	no
1.13 Algorithms	ok	partially
1.14 Auxiliary Data	ok	no
1.15 Processing Chain Provenance	n.a.	no
1.16 Data Access	ok	ok
1.17 Overall Data Quality	n.a.	ok
2. Per-Pixel Metadata		
2.1 Metadata Machine Readability	ok	ok
2.2 No Data	ok	ok
2.3 Incomplete Testing	ok	ok
2.4 Saturation	ok	partially
2.5 Cloud	ok	ok
2.6 Cloud Shadow	ok	ok
2.7 Land/Water Mask	n.a.	ok
2.8 Snow/Ice Mask	n.a.	ok
2.9 Terrain Shadow Mask	n.a.	no
2.10 Terrain Occlusion	n.a.	no
2.11 Solar and Viewing Geometry	ok	no
2.12 Terrain Illumination Correction	n.a.	no
2.13 Aerosol Optical Depth Parameters	n.a.	tbd
3. Radiometric and Atmospheric Corrections		
3.1 Measurement	ok	no
3.2 Measurement Uncertainty	n.a.	partially
3.3 Measurement Normalisation	n.a.	no
3.4 Directional Atmospheric Scattering	ok	ok
3.5 Water Vapour Corrections	ok	ok
3.6 Ozone Corrections	n.a.	ok
4. Geometric Corrections		
4.1 Geometric Correction	ok	ok

Sun diffuser exposure

Highlight: Reduction of frequency of Sun calibrations to extend mission lifetime

Actions / results:

- All life-limited items well within planned usage except diffuser exposure time by a slight amount (until Apr 2024)
- Impact analysis of reduction of Sun calibration frequency on radiometric coefficients
- Mission decision: starting in Apr 2024, Sun calibrations are performed once every 2 months (instead of monthly)
- Radiometric stability requirement (2.5%) is not violated
- Life-limited items keep to be continuously monitored to inform any future decisions

Life-Limited Item	Consumption in current period	Total usage	Estimated minimum total lifetime	Assumed frequency of use
Shutter usage	+2,12%	14,73%	17,0 years	daily
FAD movements (includes SDH and DPH)	+2,00%	24%	15,2 years	bimonthly
Diffuser exposure time				
- based on the nominal measurement time	+3,33%	40,00%	8,5 years	bimonthly
- based on the real cyclogram duration	+3,97%	47,70%	6,9 years	bimonthly
On-board calibration equipment:				
OBCA Spc lamp 1	+1,41%	12,05%	19,3 years	biweekly
OBCA Rad lamp 1/LED 1	+3,39%	23,22%	8,1 years	weekly
FPA LEDs 1	+0,56%	6,00%	44,3 years	monthly

[Mission Quarterly Report #09, in preparation]

Lessons learned from EnMAP 2.5 yr in space

- **Expect the unexpected.** VNIR degradation during commissioning closely monitored through extensive in-orbit calibration measurements and intensive collaboration with Space Segment (OHB).
- **Good is not good enough.** Keep continuous CAL/L1B improvements and go beyond requirements in order to get the most of the instruments and provide data of the highest possible quality.
- **Reach out to and hear users.** Close interaction with Science Segment (GFZ) and user feedback crucial to improve L1B, L1C and L2A products.
- **Consider Moon for calibration.** The Moon is a valuable complementary target for spectral and radiometric calibration, so consider it during the design of the mission.
- **Do not underestimate anomaly handling.** Data quality checks after small payload glitches are essential but time-consuming.
- **Monitor and react quickly.** Continuous instrument monitoring motivated change of Sun calibration frequency to extend estimated mission lifetime.
- **Inter-mission cooperation.** Extensive in-orbit calibration and product harmonization are needed to derive meaningful uncertainties and make intercomparison of data from multiple missions.

Seed questions

Replies from EnMAP GS PCV Team

Q: How many vicarious calibration sites might be needed worldwide to ensure accurate characterization of the radiances and reflectances (L1B and L2 products) returned by spectral imaging missions? And what are the core measurements that should be made at these sites (and uncertainty/performance requirements)?

- Separate CAL sites (with clear atmosphere and bright homogeneous surfaces) and VAL sites (more dense atmospheres, various surface materials).
- CAL sites: Existing RadCalNet and Hypernets sites are fine, but dark non-water site is missing.
- VAL sites: Many more sites are needed to cover extensive range of atmospheric conditions.
- Measurements: BOA reflectance (≤3% uncertainty) and simulated TOA radiance (≤5% uncertainty) with characterized uncertainties (including error correlations between bands), AOT, aerosol type, WV, characterized (measured or modelled) site BRDF.

Q: What are the main challenges in harmonizing CAL/VAL approaches across different EO missions, sites, and campaigns, and how can these be addressed?

- Similar but not identical product definitions, observation configurations, calibration procedures and validation protocols across missions.
- Coordination across missions and validation campaigns is time consuming.
- Way forward: product harmonization, reference data usable by multiple missions with well characterized uncertainties, projects like CCVS (with experts from multiple institutions).

Q: What is currently missing to carry out holistic and all-encompassing CAL/VAL activities, and how, for example with which innovations, can this be supported?

- Comparison with reference data is frequently hampered by underlying assumptions (e.g., observation geometry) whose effect is unknown.
- Realization of gold standard references on-ground and in space (e.g., TRUTHS and CLARREO missions for cross-validation).
- Sustainable and reliable infrastructures with high data availability and long-term funding.

Q: How can emerging technologies, such as artificial intelligence and machine learning, be leveraged to improve the accuracy and efficiency of calibration and validation processes?

- AI/ML can help in specific tasks (e.g., identifying outlier scenes, speeding-up simulation or correction steps, etc).
- Not clear how AI/ML may take a central role in improving the accuracy of calibration and validation, which should rely on the physical understanding of the measurements and corresponding uncertainties.

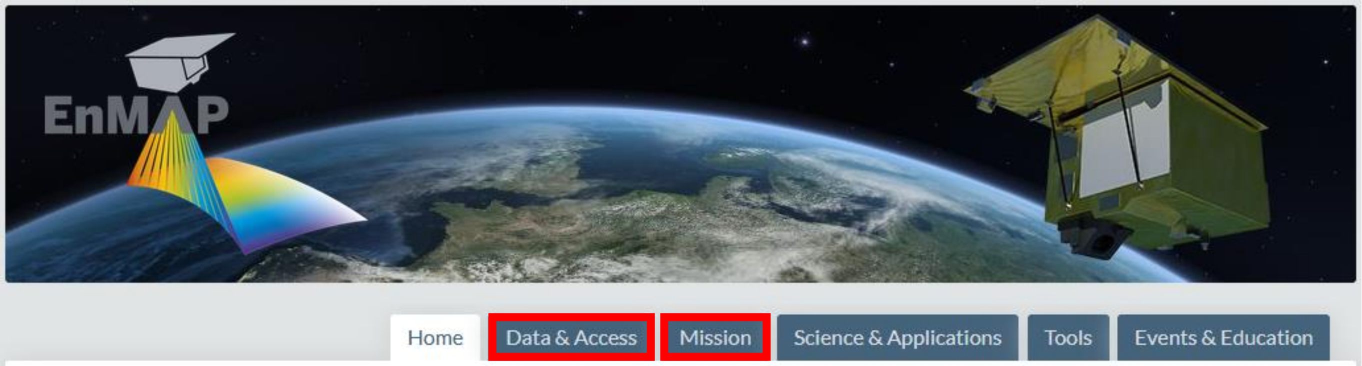
Acknowledgements

This research was supported by the DLR Space Agency with funds of the German Federal Ministry of Economic Affairs and Climate Action on the basis of a decision by the German Bundestag (50 EE 0850, 50 EE 1923 and 50 EE 2108).

Useful links:

- Tasking orders and catalog browsing:
  https://planning.enmap.org/
- Mission quarterly reports:
  https://www.enmap.org/mission/
- ICDs, ATBDs, FAQ, change log:
  https://www.enmap.org/data_access/

https://www.enmap.org/



BACKUP SLIDES

Destriping of L1B products

Highlight: Destriping at L1B level to remove effect below requirements but visible and important for users

Actions / results:

- In-depth analysis of striping and comparison of different destriping algorithms together with Science Segment
- Calibration-based destriping not possible, so statistics-based algorithm (by GFZ) selected for implementation
- Across-track destriping implemented in processor version V01.02.00 (Mar 2023)
- SWIR along-track striping due to microvibrations under investigation