Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

EnMAP Ground Segment

Mission Quarterly Report #10
01.10.2024 to 31.12.2024

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The document is publicly available via www.enmap.org.

CHANGE RECORD

Version	Date	Chapter	Comment
1.0	20.04.2025	6.2.1	Addedmore details about Geoservice data products
		7.2.2	Added more details on the interpretation of the Solar diffuse use
	20.04.2025	7.5.3	Updated the description of the SNR
	20.04.2025	All	First issue of Mission Quarterly Report #10 corresponding to 01.10.2024 to 31.12.2024.

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1 Introduction

1.1 Purpose

This mission quarterly report (MQR) states information on the EnMAP mission status with regard to the registered user community, announcements-of-opportunities and observations as well as the status of the user interfaces, satellite (platform and payload), ground stations (S-band and X-band), processor (Archive, Level 1B, Level 1C, Level 2A (land and water)), calibration (spectral, radiometric, geometric), data quality control and validation of EnMAP.

Please visit www.enmap.org for further information on EnMAP.

1.2 Scope

This 10th Mission Quarterly Report (MQR) applies to the operations of EnMAP in the reporting period of Routine Phase (RP) from **01.10.2024 to 31.12.2024 (Q4 2024)**.

2 References

Reference Identifier	**Document Identifier and Title**
[1]	L. Guanter et al. (2015) The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation. Remote Sensing, Issue 7, pp. 8830-8857.
[2]	EN-GS-UM-6020 Portals User Manual, Version 1.4
[3]	EN-PCV-ICD-2009 Product Specification, Version 1.8
[4]	EN-PCV-TN-4006 Level 1B ATBD, Version 1.9
[5]	EN-PCV-TN-5006 Level 1C ATBD, Version 1.6
[6]	EN-PCV-TN-6007 Level 2A (land) ATBD, Version 2.2
[7]	EN-PCV-TN-6008 Level 2A (water) ATBD, Version 3.1
[8]	Chabrillat, S. et al. (2022) EnMAP Science Plan. EnMAP Technical Report, DOI: 10.48440/enmap.2022.001
[9]	Storch, T.; Honold, H.-P.; Chabrillat, et al. The EnMAP imaging spectroscopy mission towards operations. Remote Sens. Environ. 2023, 294, 113632. DOI: 10.1016/j.rse.2023.113632

Table 2-1 References

3 Terms, Definitions and Abbreviations

Terms, definitions and abbreviations for EnMAP are collected in a database which is publicly accessible via Internet on www.enmap.org.

An Earth observation of swath length $n \times 30$ km (and swath width 30 km) is separated into n tiles of size 30 km × 30 km.

4 Mission

4.1 Mission Objectives

The primary goal of EnMAP (Environmental Mapping and Analysis Program) is to measure, derive and analyze quantitative diagnostic parameters describing key processes on the Earth's surface [1].

During the mission operations, with the successful launch on 1st of April 2022 and an expected operational mission lifetime of at least 5 years, EnMAP will provide valuable information for various application fields comprising soil and geology, agriculture, forestry, urban areas, aquatic systems, ecosystem transitions.

4.2 Mission Description

The major elements of the EnMAP mission are the EnMAP Space Segment, built by OHB System AG and owned by the German Space Agency at DLR, the EnMAP Ground Segment built and operated by DLR institutes DFD, MF, RB, and the EnMAP User and Science Segment represented by GFZ. The project management of the EnMAP mission is responsibility of the German Space Agency at DLR.

The EnMAP Space Segment is composed of

- the platform providing power and thermal stability, orbit and attitude control, memory, S-band uplink/downlink for TM/TC data transmission/reception, X-band downlink for payload data transmission, and
- the payload realized as a pushbroom imaging dual-spectrometer covering the wavelength range between 420 nm and 2450 nm with a nominal spectral resolution ≤ 10 nm and allows in combination with a high radiometric resolution and stability to measure subtle reflectance changes.

The EnMAP satellite is operated on a sun-synchronous repeat orbit to observe any location on the globe with comparable illumination conditions. This allows a maximum reflected solar input radiance at the sensor with an acceptable risk for cloud coverage.

The EnMAP Ground Segment is the interface between Space Segment and User and Science Segment. It comprises functionalities to

- perform planning of imaging, communication and orbit maneuver operations, provision of orbit and attitude data, command and control of the satellite, ground station networks (in particular: Weilheim, Germany, for S-band and Neustrelitz, Germany, for X-Band), receive satellite data, perform long-term archiving and delivery of products, and
- perform processing chain (for systematic and radiometric correction, orthorectification, atmospheric compensation), instrument calibration operations, and the data quality control of the products.

The EnMAP mission interfaces to the international science and user community through the EnMAP Portal www.enmap.org with official information related to EnMAP by DLR and GFZ-Potsdam (as the document in hand) and links for ordering observations and products.

The EnMAP Science Segment is represented by the EnMAP Science Advisory Group chaired by the mission principal investigator at the GFZ-Potsdam. The Science Segment addresses aspects such as

- supporting and performing validation activities to improve sensor performance and product quality
- developing scientific and application research to fully exploit the scientific potential of EnMAP [8] including provision of software tools for EnMAP data processing and analyses (EnMAP-Box) and provision of teaching and education materials (HYPERedu)

- Organizing workshops, summer schools and in general information, training and networking activities for the user community

The EnMAP User Segment is the community of German and international users ordering acquisitions and accessing products of EnMAP.

4.3 Mission Status Summary

The mission successfully finished the commissioning phase (CP) on 01.11.2022 [9] and entered its routine phase (RP) on 02.11.2022. In the reporting period, from 01.10.2024 to 31.12.2024, there have been no major issues affecting the instrument or the satellite. The mission has been operating normally with the exception of 2 outages caused by the Hyperspectral Instrument (HSI) going to SAFE ERROR for different reasons. A total of 23 days resulted in no acquisitions from the 92 days that comprised the reporting period. Partial loss of acquisitions for a few hours resulted also from the 2 “DSHA SAFETY MODEs” that happened during this period on 14. October and 11. November. Like in previous occasions, no consequences for the mission or the data quality have been observed after these events. Two Sun calibrations were performed in this period separated by a short interval after the analysis of the first one showed a small spectral shift that is attributed to slight increase of temperatures during a check performed with the satellite GYRO2 during the period 14-18 November. The second calibration showed total agreement with previous measurements and was used to derived updated calibration coefficients. At the end of the period, the back-to-back mode is fully integrated and working without problem in the EnMAP planning system and it is used regular in one out of 4 acquisitions performed. Like in previous quarters the mission is regularly reaching and surpassing the initial maximum acquisition capacity of 5000 km / day.

In this period, 1481 Earth observations of 30 km swath width and up to 990 km swath length were successfully performed which resulted in 17894 archived Earth observation tiles of 30 km × 30 km and 25 calibration acquisitions. In addition, 15501 products were delivered from catalog orders. In total, 14074 Earth observations were performed until 31.12.2024 by the EnMAP team and the 4311 registered Science users. This results in 117349 archived Earth observation images (157482 products including the different versions of the re-processed products) and 216923 Earth products delivered from observations requests (118583) and catalogue orders (98340) since the start of the mission. More details are presented in Section 5 and 6.

The following limitations are applicable at 31.12.2024:

- Striping effects in SWIR data in the along-track direction more visible in uniform areas with a strong spectral gradient.

Other effects observed in the data by our Quality Control team are reported in section 7.6 while they are investigated in more detail.

The following changes were implemented in the reporting period:

- Re-processing of archived products is complete. The reprocessed products can be identified with **archived version ≥ 01.03.01** in the EnMAP archive. Re-processed products benefit from improved co-registration accuracy, improved absolute geometric performance and addition of VC-AUX products for improved data screening. For more details on geometric performance check Section 7.6.3. In future quarters, previous archived versions will be removed and only the latest archived version of the products (≥ 01.03.01) will be shown in EOWeb.

- New processor version (V01.05.02) with the following changes:

  - Taking the water vapor of adjacent tiles into account for the selection of radiative transfer LUTs. This should result in less inconsistencies between neighboring L2A tiles from the same datatake.

  - Fixed the influence of the scene’s border on the adjacency correction.

  See also Section 7.4 and https://www.enmap.org/data/doc/EnMAP_processor_changelog.pdf

In addition, in August 2024 it was announced the availability of EnMAP products through the EOC Geoservice (https://geoservice.dlr.de/) and the EOlab platform (https://eo-lab.org/). These possibilities allow the direct download of EnMAP L2A products generated by the EnMAP Ground Segment with a standard set of parameters. Since these L2A products are already processed, users can directly download these products without waiting times, allowing a fast way to get large amounts of EnMAP products from the mission archive. Notice that both EOC Geoservice and EOlab are not part of the standard services offered by the EnMAP mission and would require registration in these additional services. More information on the number of products downloaded through Geoservice can be found in section 6.2.1.

The following changes are expected to be performed in the next quarters:

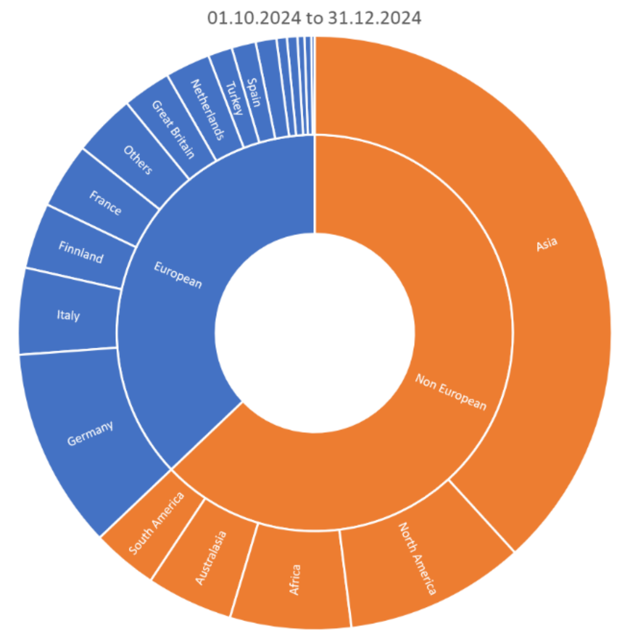
- Correction of radiometric striping in the along-track direction.
- Change of the minimum strip length for tasking orders from 1 tile to 3 tiles. A compensation measure will be implemented to compensate the quota of the existing proposals after introducing the change.
- Implementation of new linearity calibration (and updated calibration) to improve the VNIR-SWIR matching between spectrometers, specially at low radiances.
- Availability of Cat-2 role for the commercial user community.

5 Users and Announcements-of-Opportunities

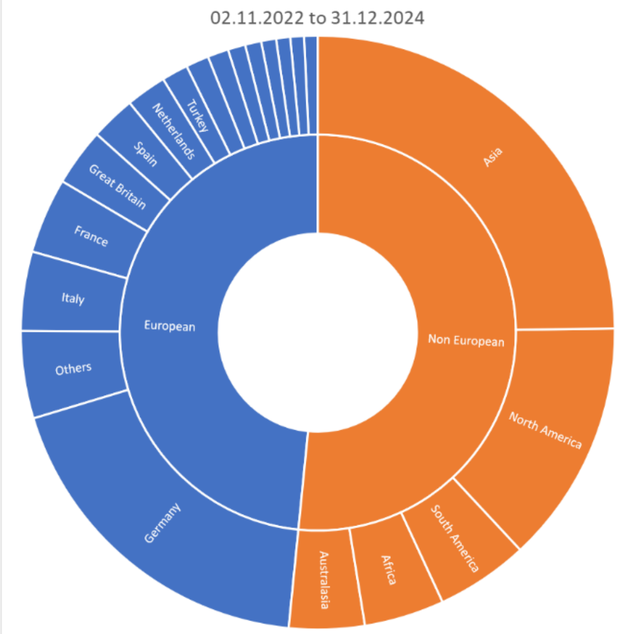
5.1 Users

	Country/Continent (No of Countries) *(of reporting period) (since beginning of routine phase)*	Reporting Period 01.10.2024 to 31.12.2024	Since beginning of routine phase until 31.12.2024 (end of reporting period)
Total European Users	Europe *(21)(35)*	197	2088
European	• Germany	58	809
	• Italy	25	186
	• France	19	177
	• United Kingdom	14	135
	• Spain	7	105
	• Netherlands	13	95
	• Portugal	3	32
	• Turkey	7	62
	• Greece	0	38
	• Belgium	6	41
	• Poland	1	54
	• Austria	2	33
	• Finland	19	49
	• Switzerland	2	35
	• Norway	3	32
	• Others (9)(20)	18	205
Non European	North America *(5)(11)*	52	573
	South America *(5)(8)*	19	217
	Asia *(20)(34)*	203	1068
	Africa *(17)(31)*	35	188
	Australia + New Zealand *(2)*	25	177
	Total *(70)(122)*	**524**	**4311**

Table 5-1 Number of registered users per continent **(number of user countries during reporting period)**



Reporting Period 01.10.2024 to 31.12.2024 with a total of 524 Users of 70 different countries.



Since beginning of operational phase until 31.12.2024 (end of reporting period) with total of 4311 Users of 122 different countries.

Figure 5-1 Number of registered users per country

Registered users belong to different categories, therefore e.g. All/World ≠ Science/World + Others/World.

User per Category		New within reporting period 01.10.2024 to 31.12.2024	Since beginning of routine phase start until 31.12.2024 (end of reporting period)
Registered users	Total	524	4311
	with role assignment*	403	3296
Cat-1 Science	Total	330	2641
	AO Process 00001*	329	2537
	AO Process 00002*	0	620
	AO Process 00003*	1	197
Cat-1 Distributor**	Total	328	2595

Table 5-2 Number of registered and approved users per category (Cat-1 Science and Cat-1 Distributor)

*Registered users with at least one active user role assignment

**Catalogue User, ordering EnMAP data from archive

5.2 Announcements-of-Opportunities

Announcement-of-Opportunity	New within reporting period 01.10.2024 to 31.12.2024			Since beginning of routine Phase until 31.12.2024 (end of reporting period)		
	Proposals	Total tiles requested	Total tiles granted	Proposals	Total tiles requested	Total tiles granted
A00001	69	9867	1919	587	52249	19508
A00002	2	1	5	126	20561	9390
A00003	0	0	0	4	151	97
Total	70	9868	1924	717	72961	28995

Table 5-3 Number of released science proposals per Announcement-of-Opportunity (AOs#) and total number of requested and granted tiles per AO#.

Icon	Topic	New within reporting period 01.10.2024 to 31.12.2024			Since beginning of routine Phase until 31.12.2024 (end of reporting period)		
		Proposal	Total tiles requested	Total tiles granted	Proposal	Total tiles requested	Total tiles granted
	VEGETATION	20	4495	337	275	36410	12888
	GEO/SOIL	28	2155	320	228	11999	4856
	WATER	5	312	48	86	8779	3075
	SNOW/ICE	3	240	75	17	2230	881
	URBAN	3	304	26	12	1138	341
	ATMOSPHERE	7	1318	84	36	5303	1498
	HAZARD/RISK	2	5	15	14	357	310
	METHODS	0	0	0	15	945	542
	CAL/VAL	2	1039	1019	34	5800	4604
	Total	**70**	**9868**	**1924**	**717**	**72961**	**28995**

Table 5-4 Number of accepted science proposals and total number of requested and granted tiles per topic

6 Archived and Delivered Observations

The following table shows the number of archived Earth Observation and Calibration products and their sizes within the specified time frames. Reason for “Archived = No” is that datatakes were commanded but no data arrived at the Processing System HSI.

Type	Archived		Reporting Period 01.10.2024 to 31.12.2024		Since beginning of Commissioning Phase until 31.12.2024 (end of reporting period)	
			Number Tiles / Observations	Size (in GB)	Number Tiles / Observations	Size (in GB)
Earth Observation (EO)	Yes	Total	17894 / 1481	8719.17	157482 / 14074	76735.93
		Average / Day	194.5 / 16.09	94.77	156.54 / 13.99	76.27
	No	Total	72		1019	
		Average / Day	0.78		1.01	
Calibration (CAL)	Yes	Total	25	104.39	394	1645.23
		Average / Day	0.27	1.13	0.39	1.63
	No	Total	1		4	
		Average / Day	0.01		0.0039	

Table 6-1 Number and size of archived and not archived products

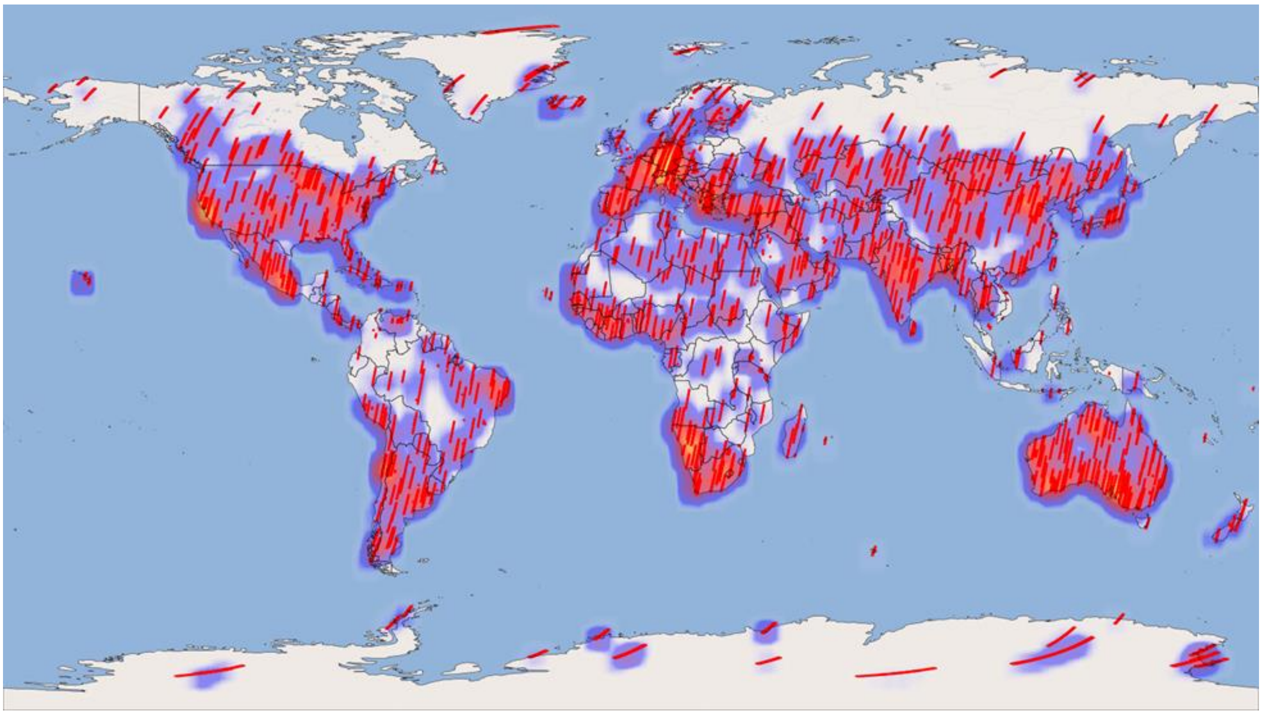
The following table shows the number of delivered products and their sizes within the specified time frames. Product deliveries result either directly from acquisition orders (“Observation”) or catalog orders (“Archive”).

Type	Delivered		Reporting Period 01.10.2024 to 31.12.2024		Since beginning of Commissioning Phase until 31.12.2024 (end of reporting period)	
			Number Tiles / Observations	Size (in GB)	Number Tiles / Observations	Size (in GB)
Earth Observation (EO)	Observation	Total	20306 / 1355	9201.44	118583 / 11079	52503.22
		Average / Day	220.71 / 14.72	100.01	117.87 / 11.01	52.19
	Archive	Total	15501	97341.95	98340	570031.62
		Average / Day	168.48	1058.06	97.75	566.63
Calibration (CAL)	Observation	Total	25	88.79	225	963.09
		Average / Day	0.27	0.96	0.22	0.95
	Archive	Total	0	0.0	67	3486.14
		Average / Day	0.0	0.0	0.06	3.46

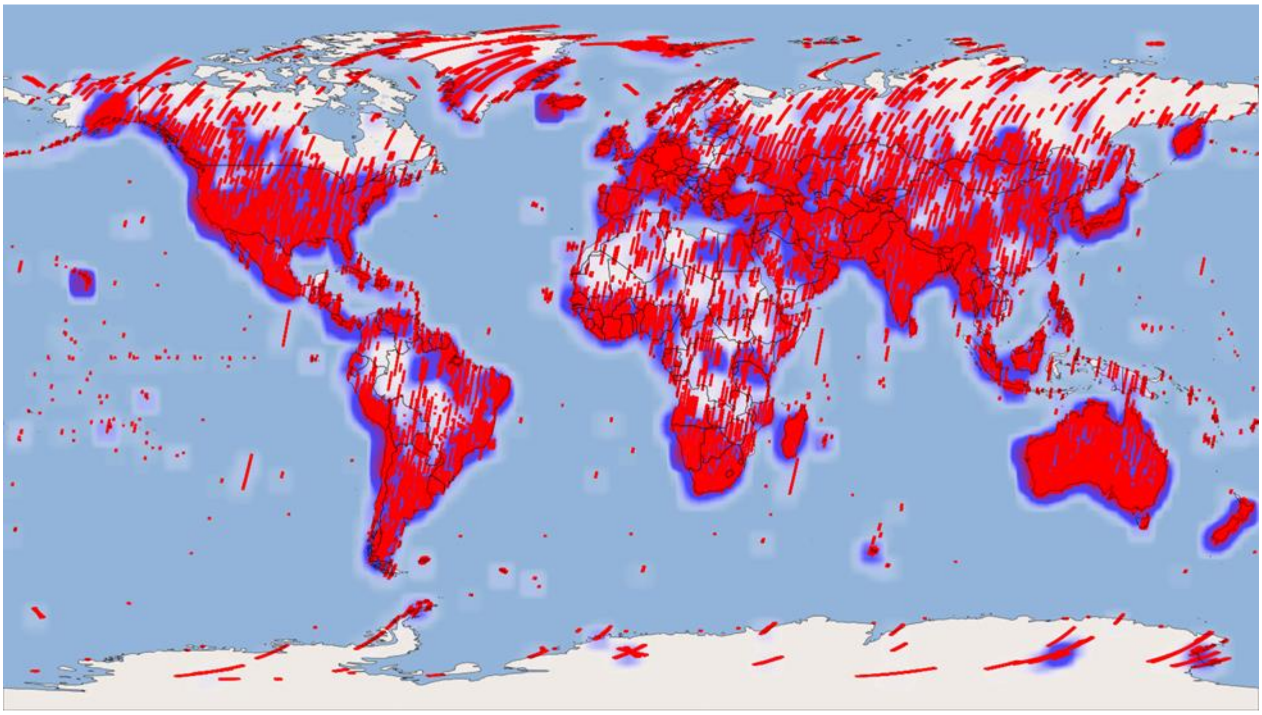
Table 6-2 Number and size of delivered products

6.1 Archived Observations

The following figures show the heatmaps for the whole world and for Europe within the specified time frames. The heatmaps represent the frequencies of products at a geographic location, where the number of products increases from blue over red to yellow.

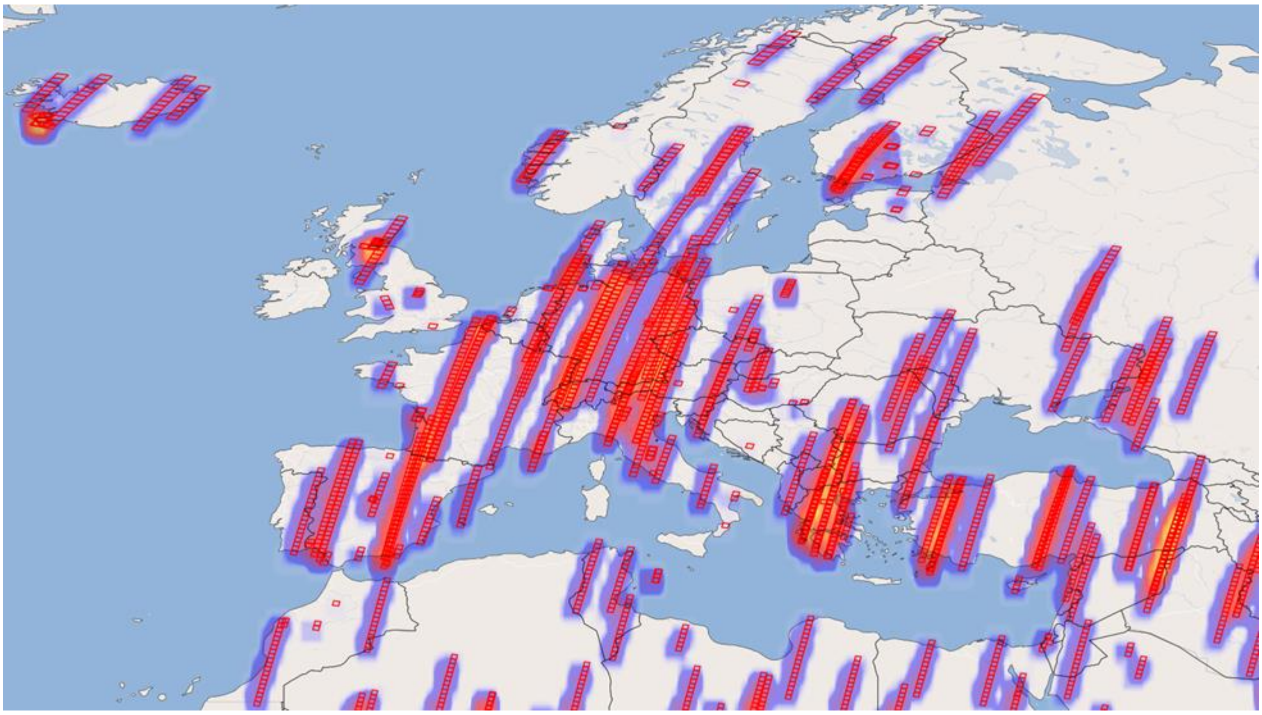


reporting period 01.10.2024 to 31.12.2024

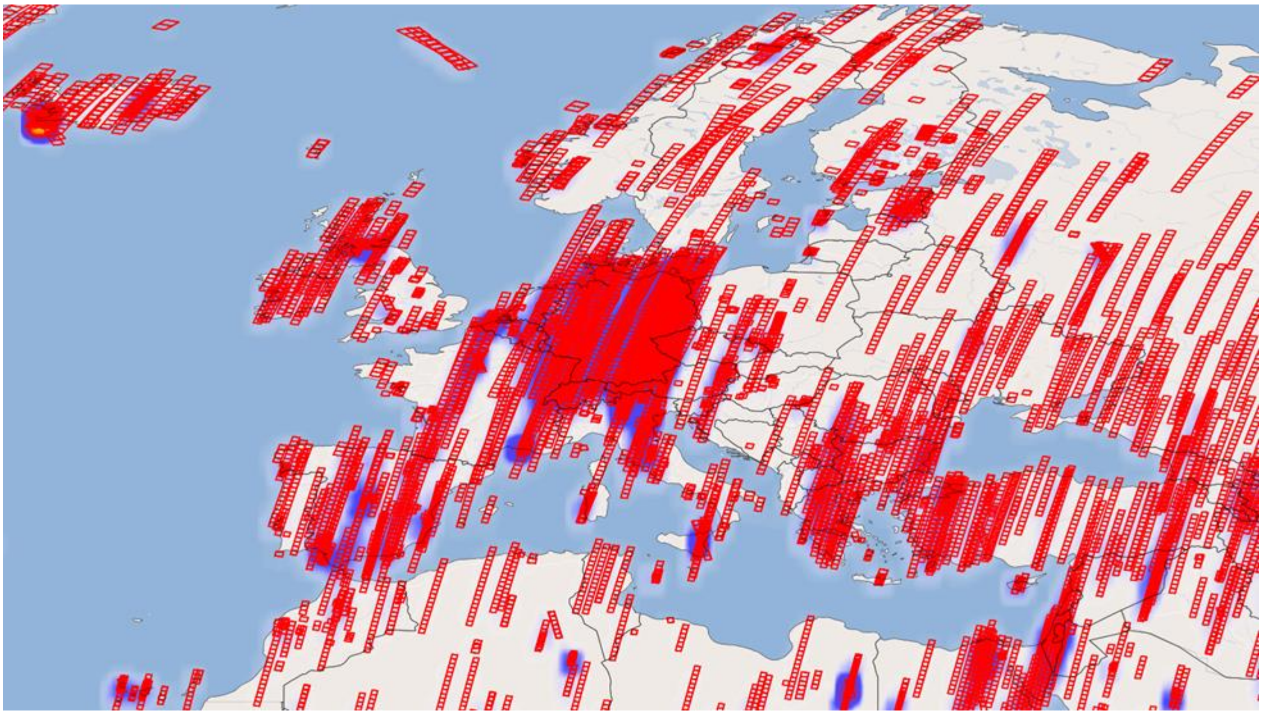


reporting period 2022-04-01 to 31.12.2024 includes commissioning phase acquisitions and different versions of the same tiles)

Figure 6-1 Geographic location of all Earth observation tiles archived, World



reporting period 01.10.2024 to 31.12.2024 Europe



reporting period 2022-04-01 to 31.12.2024 Europe (includes commissioning phase acquisitions)

Figure 6-2 Geographic location of all Earth observation tiles archived, Europe

The following figures show the distribution of cloud coverage for the archived products.

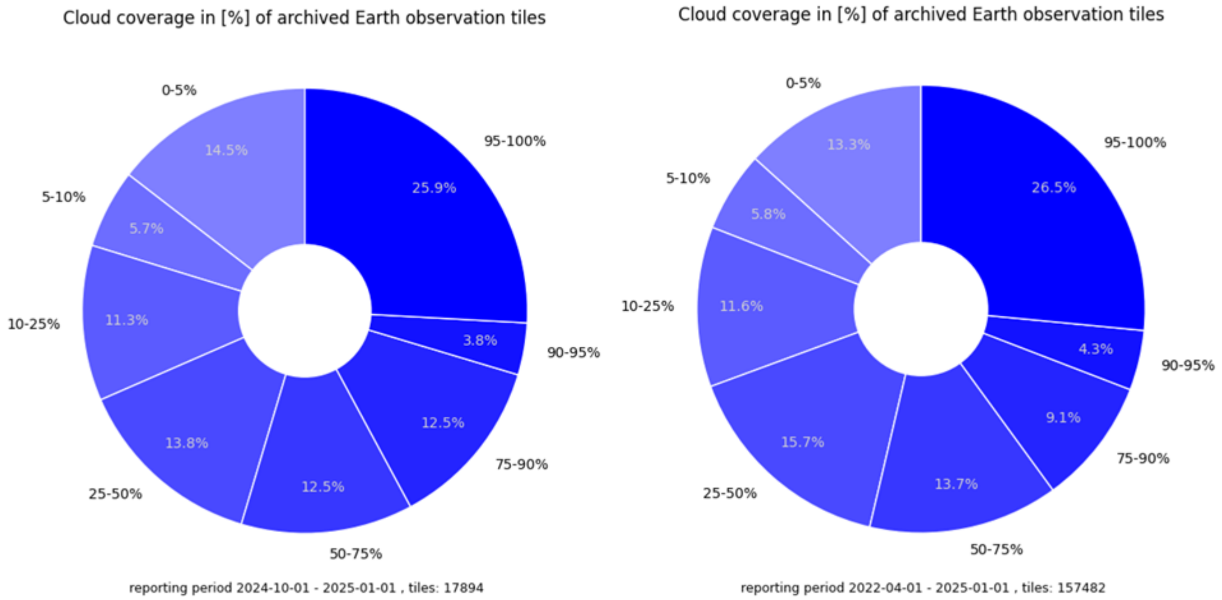


Figure 6-3 Cloud coverage in [%] of archived Earth observation tiles

The following figures show the distribution of observation angles for the archived products.

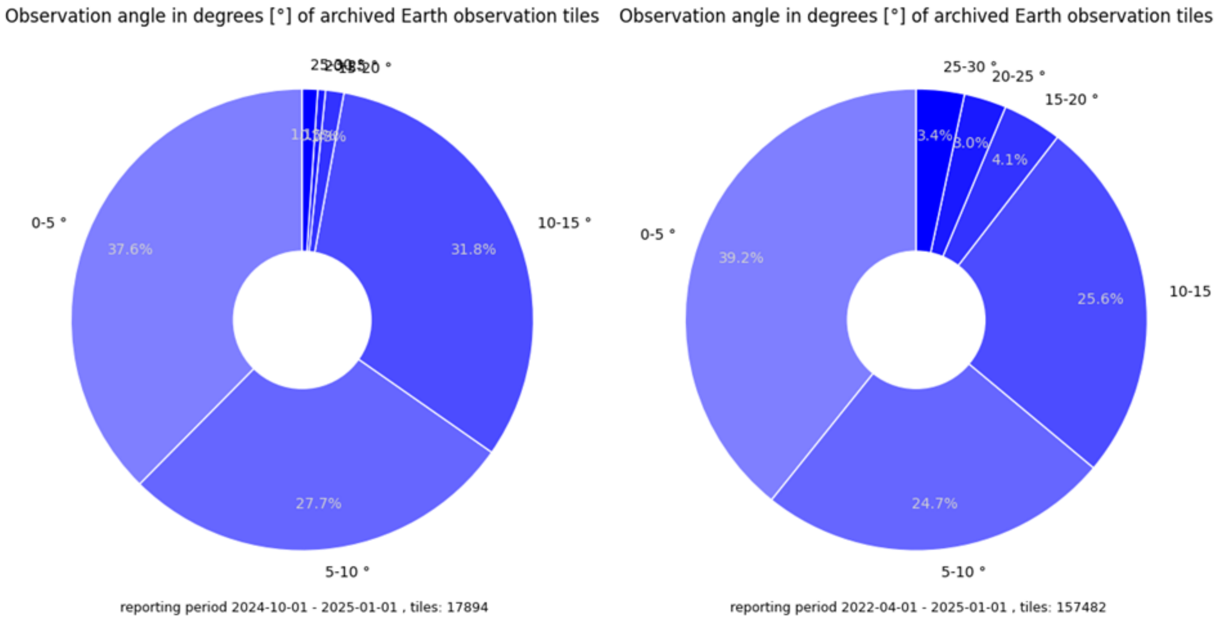


Figure 6-4 Observation angle of archived Earth observation tiles

6.2 Delivered Observations

The following figures show the distribution of processing level of the delivered products from acquisition orders.

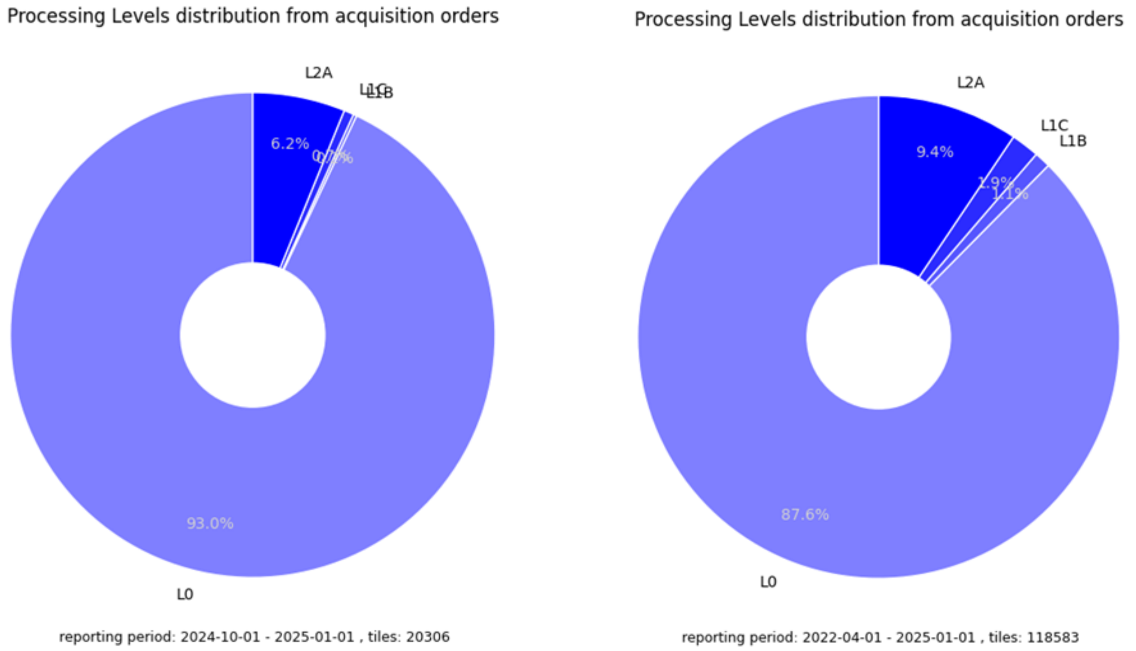


Figure 6-5 Levels of delivered Earth observation tiles from acquisition orders

The following figures show the distribution of processing level and correction type (for L2A) of the delivered products from catalog orders.

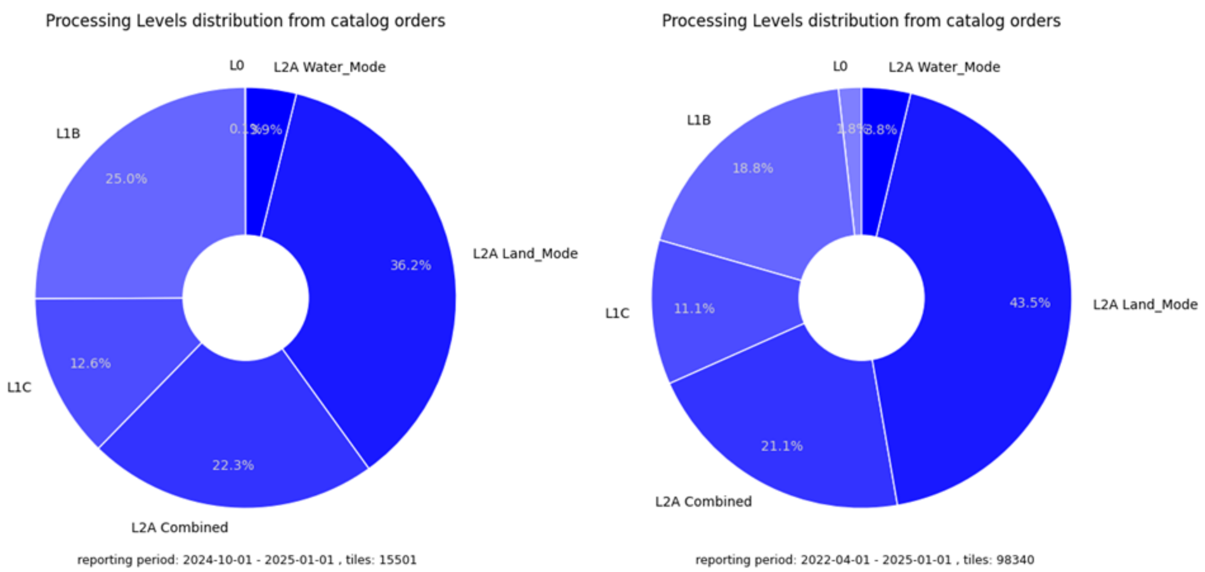


Figure 6-6 Levels of delivered Earth observation tiles from catalog orders

6.2.1 Delivered L2A products from the Download service (EOC Geoservice)

In order to reduce the workload of the system, the Ground Segment produces L2A products already processed with standard parameters that are available for direct download using the EOC Geoservice and the EOLab platform.

All recorded data is processed to L2A ARD format using EnMAP's Ground Segment processors and default parameters, saving computational and waiting time. The default processing parameters of the L2A ARD are the following:

Product_Format = GeoTIFF+Metadata
Map Projection = UTM_Zone_of_Scene_Center
Image Resampling = Bilinear_Interpolation
Correction Type = Land_Mode
Cirrus Haze Removal = No
Band Interpolation = No
Terrain Correction = Automatic
Season = Automatic
Ozone column = Automatic

Table 6-3 Processing parameters used for the L2A ARD products in Geoservice / EOLab

In addition, take into account that:

- the versions of the L2A ARD products may differ depending on their generation time. The processor changelog (https://www.enmap.org/data/doc/EnMAP_processor_changelog.pdf) provides an overview of the software changes
- No L2A-water products are available as L2A ARD products in Geoservice. For the moment water processing is only available using the on-demand processing options in EOWeb.
- The L2A ARD archive is still being completed. It is expected that along Q2 2025 all EnMAP archive is available at Geoservice / EOLab.

The total number of downloaded L2A products using the EOC Geoservice is **487822** for this reporting period (01.10.2024 to 31.12.2024).

Product	Month	# Downloads
ENMAP-L2A	2024-10	166784
ENMAP-L2A	2024-11	199
ENMAP-L2A	2024-12	320839
Total in period		487822

Table 6-4 Absolut amount of L2A ARD product downloads in Geoservie

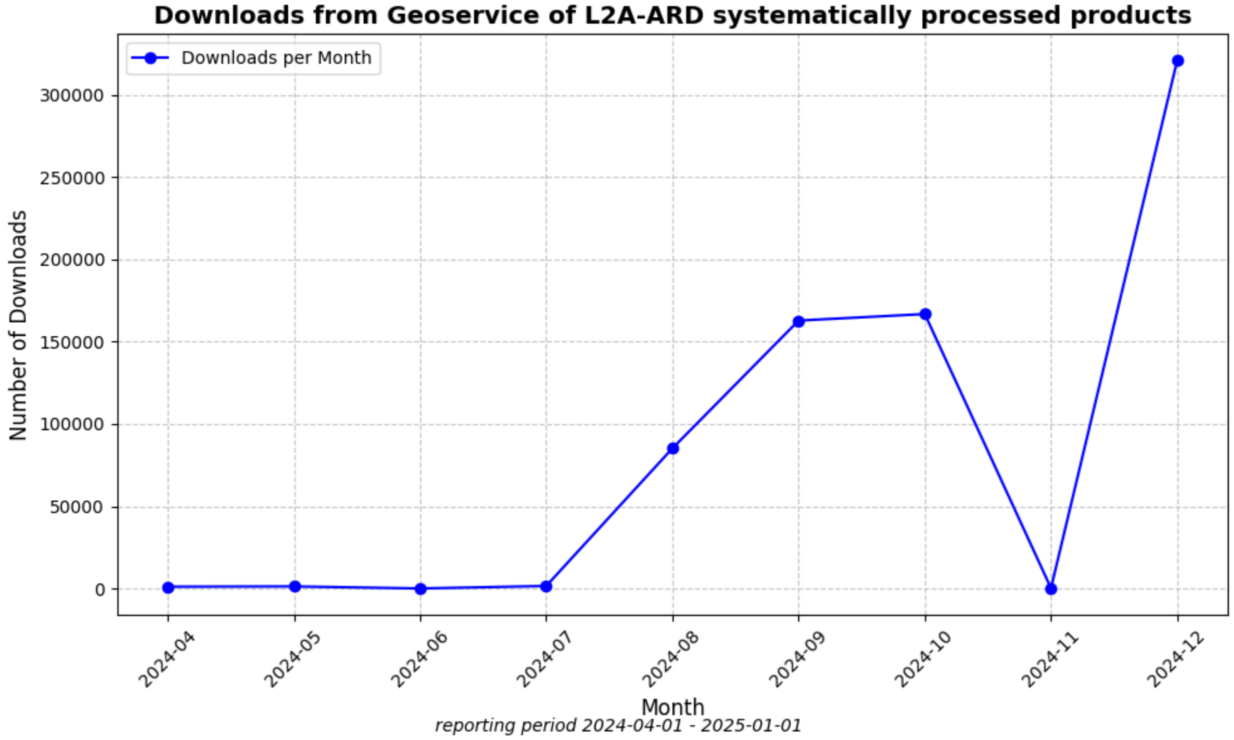


Figure 6-7 Downloads of L2A-ARD products in Geoservice per month

7 Detailed Status

7.1 User Interfaces

Further improvements to the user interfaces are continuously on-going and will be reported in this section. No important changes were introduced in the planning system, but the Ground Segment plans two important updates that will be activated during the next reporting period (Q1 2025) in the Instrument Planning Portal when submitting a EnMAP tasking order:

- Increase of the minimum tasking order size from 1 tile (30 km swath length) to 3 tiles (90 km swath length)
- Suspension of the automatic re-do option. In the future the users shall manually re-order a product if the clouds in the scene are not satisfactory for its use
- Introduction of the Cat-2 role for the commercial user community

During the reporting period the Ground Segment of EnMAP continues to update the information on future high priority observations of the EnMAP mission (*Foreground Mission*). The tool displaying this information is available at the EnMAP web site under: https://www.enmap.org/data_tools/foreground_mission/

With this tool the users can get informed weeks in advance about future priority observations with EnMAP. Initially, a set of 10 (990km) flight-lines over Germany have been identified together with the user community and will be regularly scheduled. Since July 2024, the Foreground mission has expanded (29 flight-lines) to include additional European regions. The foreground mission continues in December 2024 with a shift to the Southern Hemisphere, Europe will only be imaged south of the Alps focusing on cloud-free images and. Campaigns are continued to be supported (mainly outside of Europe) over the European winter months.

New regular flight lines on other locations are also announced in the Foreground Mission page.

7.2 Satellite

During the reporting period two incidents in the Instrument affected the operations and caused outages in the EnMAP operations. On 08. December the HSI went to SAFE_ERROR state starting an outage that lasted until 17. December. A similar event occurred on 27. December and operations were resumed on 07. January 2025. Both events did not have consequences for the instrument and the data quality checks performed after resuming operations showed that the data quality was unaffected. Although the root-cause could not be established in the first event, it is suspected that this could be connected with a radiation event like it was the case on the second event.

In addition, two new occurrences of the known DSHA SAFETY MODES took place on 14. October and 11. November, resulting in the loss of a few hours of observation time, until a reset could be commanded.

The Back-2-Back imaging sequences are used regularly by the mission planning, allowing a fast acquisition of up to three ground targets within one large attitude maneuver. This mode is working correctly and amounts for approximately 24% of all the acquisitions performed by EnMAP in the reporting period.

7.2.1 Orbit

The reference orbit is a Sun-synchronous polar orbit with a mean local time of descending node of 11:00 hrs and a repeat cycle of 398 revolutions in 27 days at an altitude of 643 km.

The satellite orbit is controlled with respect to an Earth-fixed reference track over the entire orbit, analogous to a rim, with a control box of +/- 6 km in radial direction and +/- 22 km in normal direction. In the report interval two inclination control maneuvers (on October 21 and December 5 with +0.400 m/s) and three in-plane maneuvers (drag make-up on October 2 with +0.175 m/s, November 4 with +0.253 m/s and December 5 with +0.194 m/s) were performed.

During the reporting period, a total of 1511 ACS Precise Modes were executed on-Board, compared to 1676 during the previous quarter (see Figure 7-1). Due to the implementation of Back-to-Back Image Acquisitions, the number of ACS Precise Modes does not represent the number if performed activities anymore. By executing two or three Images as one sequence, the total number of ACS Precise Modes decreases whereas the number of Image Acquisitions remains stable or increases.

During Q4 2024, no ACS Precise Mode were aborted and no problems occurred during the commanding or execution of ACS Precise Modes for Orbit Maneuvers. One collision avoidance maneuver was executed on October 10th due to a close approach with object COSMOS-220 (NORAD-ID 03229). The resulting performance error off all maneuvers was estimated by FDS to be between -1.1% and +0.2%.

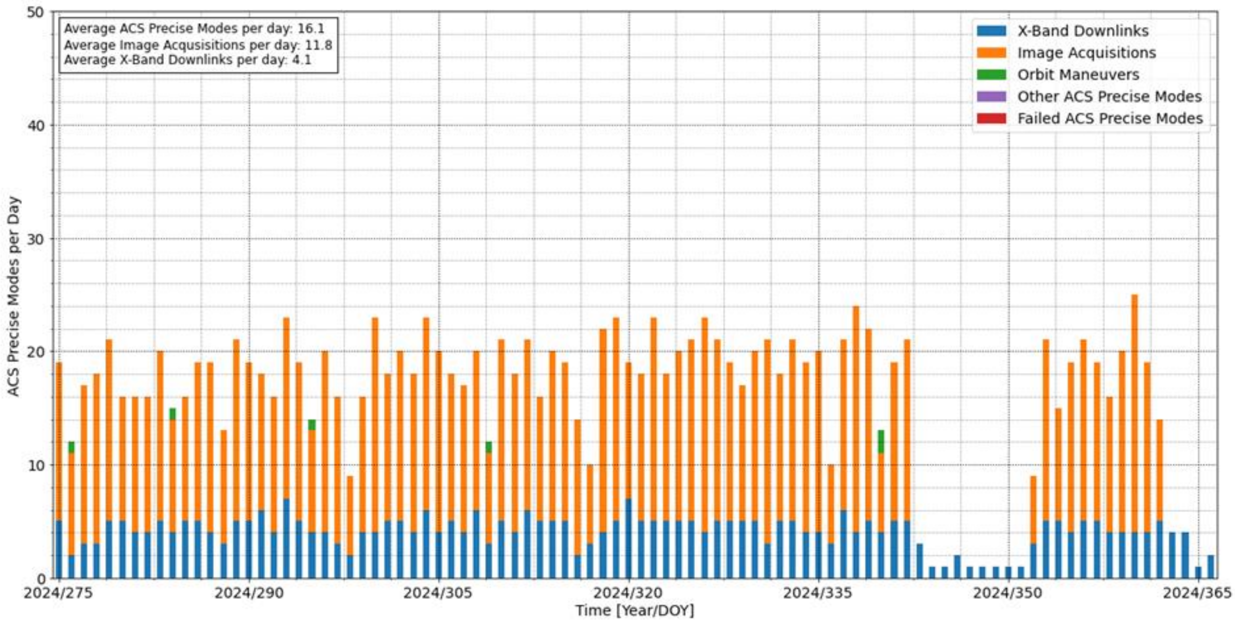


Figure 7-1 Number of ACS Precise Modes per day during Q4 2024

7.2.2 Life Limited Items

The life cycle of the life limited items is evaluated depending on their use.

Add sentence about battery/solar cells.

The life-limited items include the following optical and mechanical components:

Life-Limited Item	01.10.2024 to 31.12.2024	until 31.12.2024	Estimated minimum total lifetime / health of the system
Fuel	+0,5 kg	7,3 kg	17 years
Battery and Solar Cells(*)	nominal	nominal	Nominal
Shutter Usage	+1,74%	16,47%	16,7 years (@ daily use)
FAD movements	+2,00%	26%	15,1 years (@ bimonthly use)
Diffuser exposure time based on sole measurement time(**)	+3,98%	51.76%	8,4 years (@ bimonthly use to reach 100% originally planned used)
Diffuser exposure time based on real cyclogram duration(**)	+3,33%	43,33%	6,8 years (@ bimonthly use to reach 100% originally planned used)
On-Board Calibration Equipment Usage	On-board calibration equipment:		

- OBCA SPC lamp 1	+1,20%	13,25%	19,3 years (@ biweekly use)
- OBCA RAD lamp 1/LED 1	+2,87%	26,09%	8,2 years (@ weekly use)
- FPA LEDs 1	+0,37%	6,37%	44,4 years (@ monthly use)

Table 7-1 Status of life-limited items

(*) The Power Subsystem is working nominally and as expected. Voltage stays above any critical level.

(**) A 100% Sun diffuser exposure time corresponds to a total planned exposure of 2 hours after 5 years when performing monthly Solar calibrations. The contribution of the diffuser to the total radiometric uncertainty after reaching the reference 100% value is estimated to be **0.6%** according to the instrument manufacturer. This value is significantly below the 5% total radiometric uncertainty requirement, which indicates that the diffuser will not be a relevant contributor to the total radiometric uncertainty of the instrument even if the diffuser were to be used significantly above the originally allocated 2 hours of exposure time (reference 100% value). Nevertheless, the use of the diffuser is continuously monitored and accounted for in the Life-Limited Item list and thanks to the instrument stability the Sun calibration frequency is adjusted to reduce the number of necessary Solar calibrations.

The consumed resources are calculated based on the processed L0 product metadata, i.e. only successfully processed calibrations can be considered. The budget is supplemented with information about data takes that were aborted or lost due to transmission or technical problems.

7.2.3 Redundancies

To date, the SWIR wavelength range is covered by SWIR-A (SWIR-B can be activated using a one-time switch mechanism).

All satellite subsystems are using nominal configurations.

7.3 Ground Stations

7.3.1 S-Band

S-Band Ground Stations	01.10.2024 to 31.12.2024		
	Total Passes	Non-Routine Passes (e.g. Anomaly Handling/SW Updates)	Failed Passes
All stations (Weilheim-Germany, Neustrelitz-Germany, Inuvik-Canada, O'Higgins-Antarctica, Svalbard-Norway)	563 (182 WHM, 226 NSG, 155 INU)	9	8

Table 7-2 S-Band Ground Station Passes

7.3.2 X-Band

X-Band Ground Stations	01.10.2024 to 31.12.2024	
	Executed Passes	Successful Passes
All stations (Neustrelitz-Germany, Inuvik-Canada)	379 (281 NZ, 98 INU)	379 (281 NZ, 98 INU)

Table 7-3 X-Band Ground Station Passes

Inuvik (Canada) station is now part of the regular operations of the EnMAP Ground Segment for X-Band and S-Band downlinks. After integration, more data and more flexibility in S-band and X-band data reception is achieved, especially concerning image acquisitions over Europe.

7.4 Processors

Reference [3] provides the product specification and [4], [5], [6], [7] the algorithm theoretical basis for Level 1B, Level 1C and Level 2A (land / water).

During Q4 2024, the change log documenting the history of EnMAP processor updates continues to show the updates performed in the processing software. The document can be downloaded from the EnMAP website:

https://www.enmap.org/data/doc/EnMAP_processor_changelog.pdf

In the reporting period (01.10.2024 to 31.12.2024) the following processors version were introduced:

- Version **V01.05.02** (03.12.2024, available to users on 06.12.2024). This new EnMAP processors version introduces:
    - Taking the water vapor of adjacent tiles into account for the selection of radiative transfer LUTs. This should result in less inconsistencies between neighboring L2A tiles from the same datatake
    - Fixed the influence of the scene's border on the adjacency correction.

The following limitations are applicable as of 31.12.2024:

- The SWIR-A compressor cooler produces a micro-vibration pattern of horizontal stripes on SWIR bands with strong spectral gradients. Still, all spectral and radiometric requirements are within the specification of the mission.

The following changes are expected to be performed in the future quarters:

- Update of the linearity calibration to improve the matching between VNIR and SWIR spectrometers, specially at low radiance level.

7.5 Calibrations

Table 7-4 summarizes the radiometric calibration observations acquired in this quarter and which will be described in the rest of this section. The calibration acquisitions were generally acquired according to the routine operations plan.

Category	01.10.2024 to 31.12.2024	
	Number of Archived Observations	Size (in GB)
Total	25	90.1
Deep Space	4	5.2
Rel. Radiometric	11	42.9
Abs. Radiometric	2	2.6
Linearity	2	34
Spectral Calibration	6	5.4

Table 7-4 Number and size of archived radiometric and spectral calibration observations

The continuous degradation of the VNIR sensor was monitored and quantified. The rate of degradation is constantly decreasing as illustrated in Figure 7-2 and by the end of March 2023 it has reached the point where it is practically negligible and has been kept that way during the reporting period. It shall be noted, though, that this average trend is different at different parts of the detector as illustrated for individual pixels in Figure 7-3. The effect on the radiometric calibration coefficients of a few selected bands is shown in Figure 7-4.

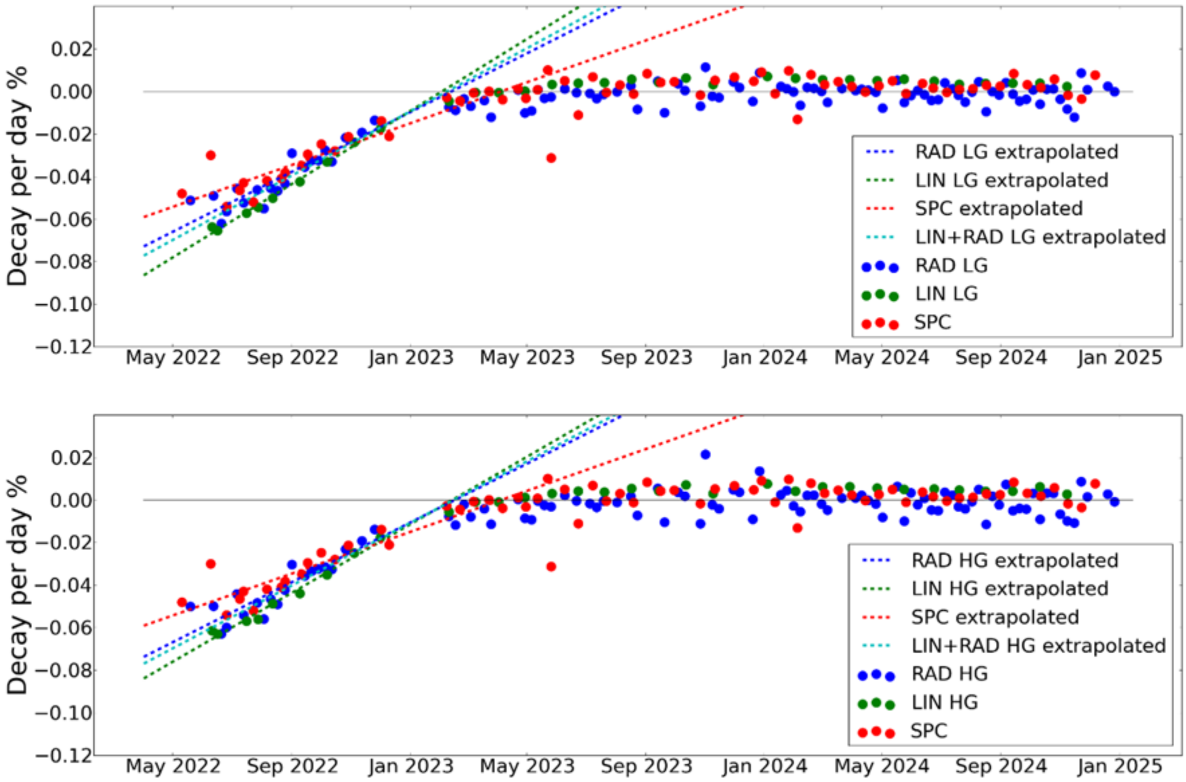


Figure 7-2 Decay per day from Lamp (RAD), Linearity (LIN) and Spectral (SPC) measurements for low gain (top) and high gain (bottom)

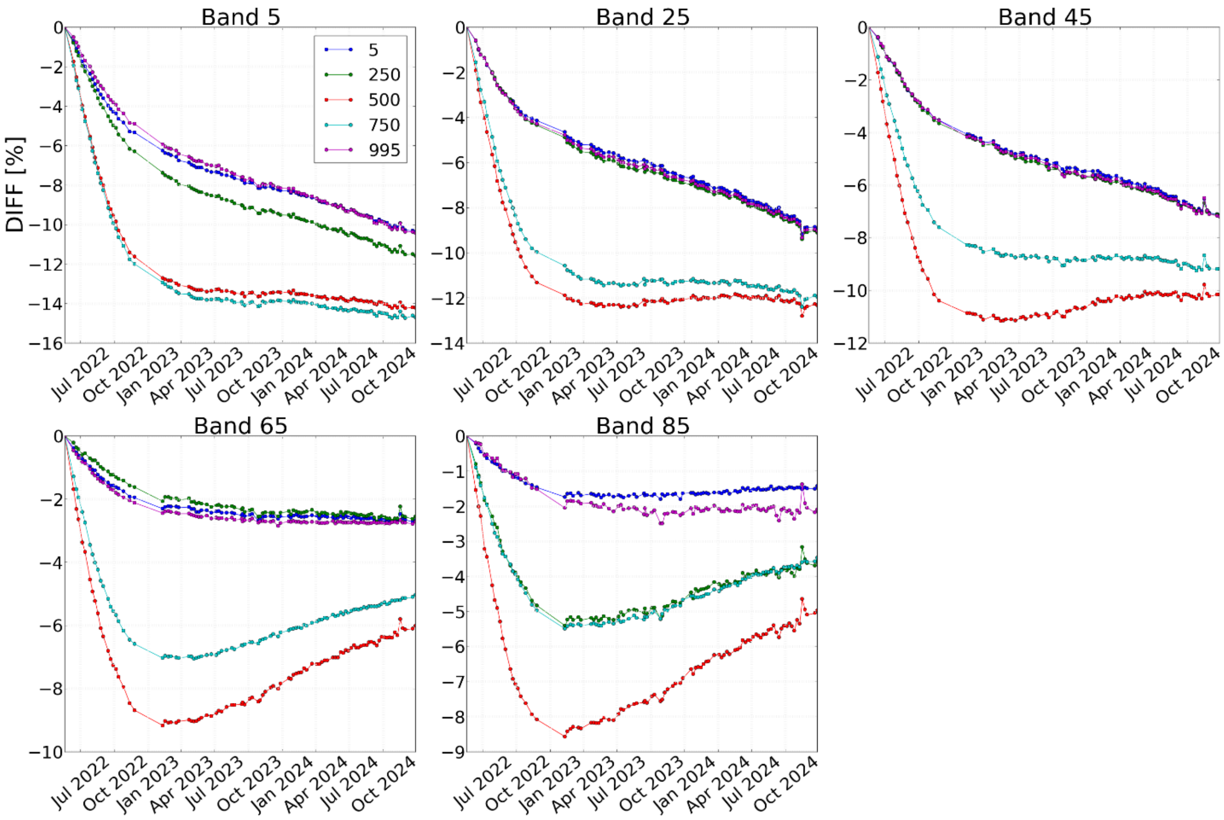


Figure 7-3 Change in percentage for individual pixels based on OBCA-Lamp measurements given for 5 bands and 5 cross track elements (coloured lines).

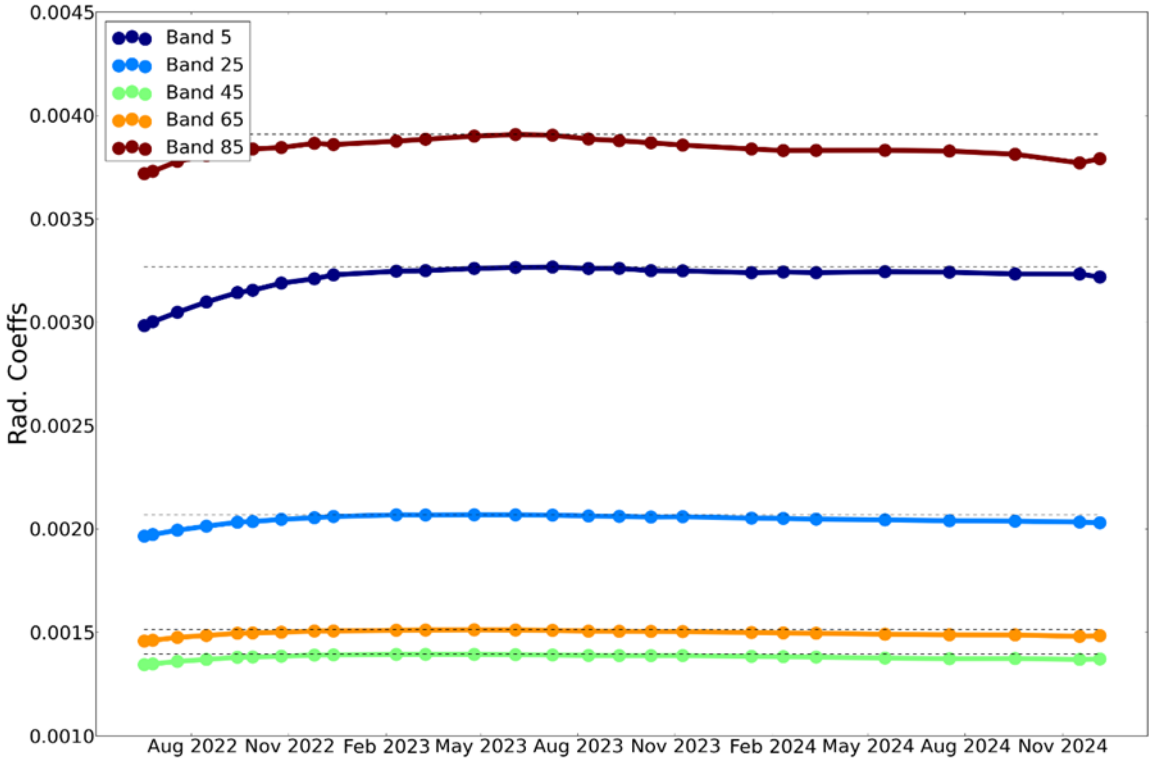


Figure 7-4 Average percentage change in the VNIR radiometric coefficients for five selected bands since launch

7.5.1 Dead Pixels

The following table shows the number and percentage of dead pixels. Figure 7-5 and Figure 7-6 show the position of the dead pixels in the focal plane of VNIR and SWIR sensors respectively. There have been no updates since 31.08.2022.

Defect Pixels	01.10.2024 to 31.12.2024	
	Number of Pixels	Percent
Total	1921	0.8
VNIR	137	0.2
SWIR	1784	1.2

Table 7-5 Number and percent of dead pixels

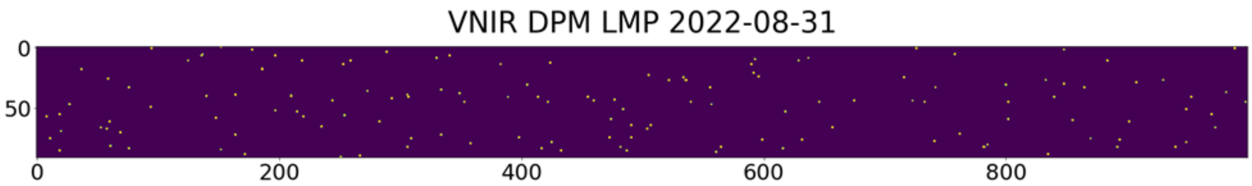


Figure 7-5 VNIR Dead Pixel Mask

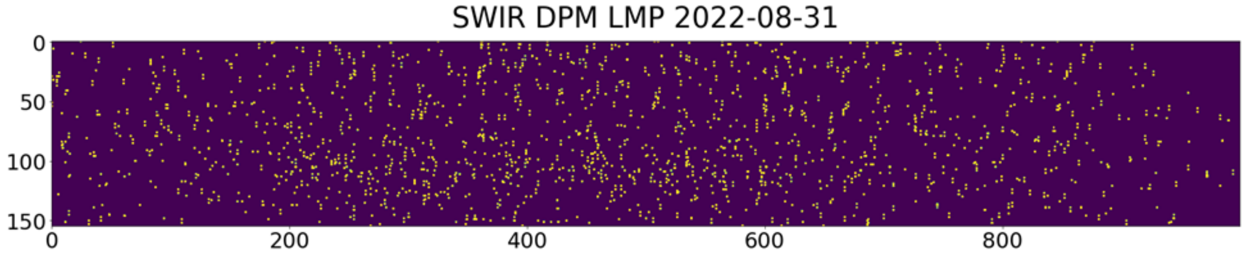


Figure 7-6 SWIR Dead Pixel Mask

There are no clusters of more than three spectrally or spatially adjacent dead pixels.

7.5.2 Spectral Calibration

Remark: In the following figures, OBCA is abbreviation for On-Board Calibration Assembly for spectral and radiometric calibrations.

Category	01.10.2024 to 31.12.2024	
	Number of Archived Observations	Size (in GB)
Total	6	5.4
Spectral Calibration	6	5.4

Table 7-6 Number and size of archived spectral calibration observations

The spectral properties – in particular center wavelength (CW) (see Figure 7-7 and Figure 7-8) and full width at half maximum (FWHM) (see Figure 7-9) for each band (spectral coordinate) and pixel (spatial coordinate) – have been characterized, considering all bands and pixels provided in Level 1B, Level 1C and Level 2A products.

The major conclusions of the monitoring of the spectral performance are summarized as follows:

- During the reporting period, 6 spectral calibration measurements were made which took place on: 12.10.2024, 25.10.2024, 08.11.2024, 22.11.2024, 06.12.2024 and 20.12.2024.
- The VNIR spectral range in this reporting period was found to be 418.4 – 993.3 nm over 91 bands (Figure 7-7). The average spectral sampling distance was 6.4 nm with a total range of 4.7 – 8.2 nm. This meets the requirement for overall wavelength coverage [HSI-POSS-0210], average spectral sampling distance [HSI-POSS-0310] and spectral sampling distance range [HSI-POSS-0320].
- The SWIR spectral range in this reporting period was found to be 902.1 – 2445.4 nm over 155 bands (Figure 7-7). The average spectral sampling distance was 10.0 nm with a total range of 7.5 – 12.0 nm. This meets the requirement for overall wavelength coverage [HSI-POSS-0210], average spectral sampling distance [HSI-POSS-0310] and spectral sampling distance range [HSI-POSS-0320].
- The spectral calibration measurements from this quarter show good temporal stability – measurements showed an absolute <0.15 nm change from the VNIR sensor and <0.20 nm change in SWIR (Figure 7-8) with respect to current spectral calibration table. All changes were below 0.5 nm between measurements for VNIR and below 0.5 nm SWIR. This meets the requirement for consecutive spectral stability [HSI-POSS-0510] and overall spectral stability [HSI-POSS-0520].
- FWHM for VNIR and SWIR (Figure 7-9) are shown below but are not recalculated inflight.
- A VNIR degradation pattern is not clearly visible between consecutive spectral reference measurements acquired in this period, but there are positive and negative changes across the detector and on average the signal appears to have increased by 0.27% across all pixels from

27.09.204 to 20.12.2024. A slightly smaller change was reported in the previous quarter (0.26%). Although small, the monitoring of this behavior will continue in the next reporting period.

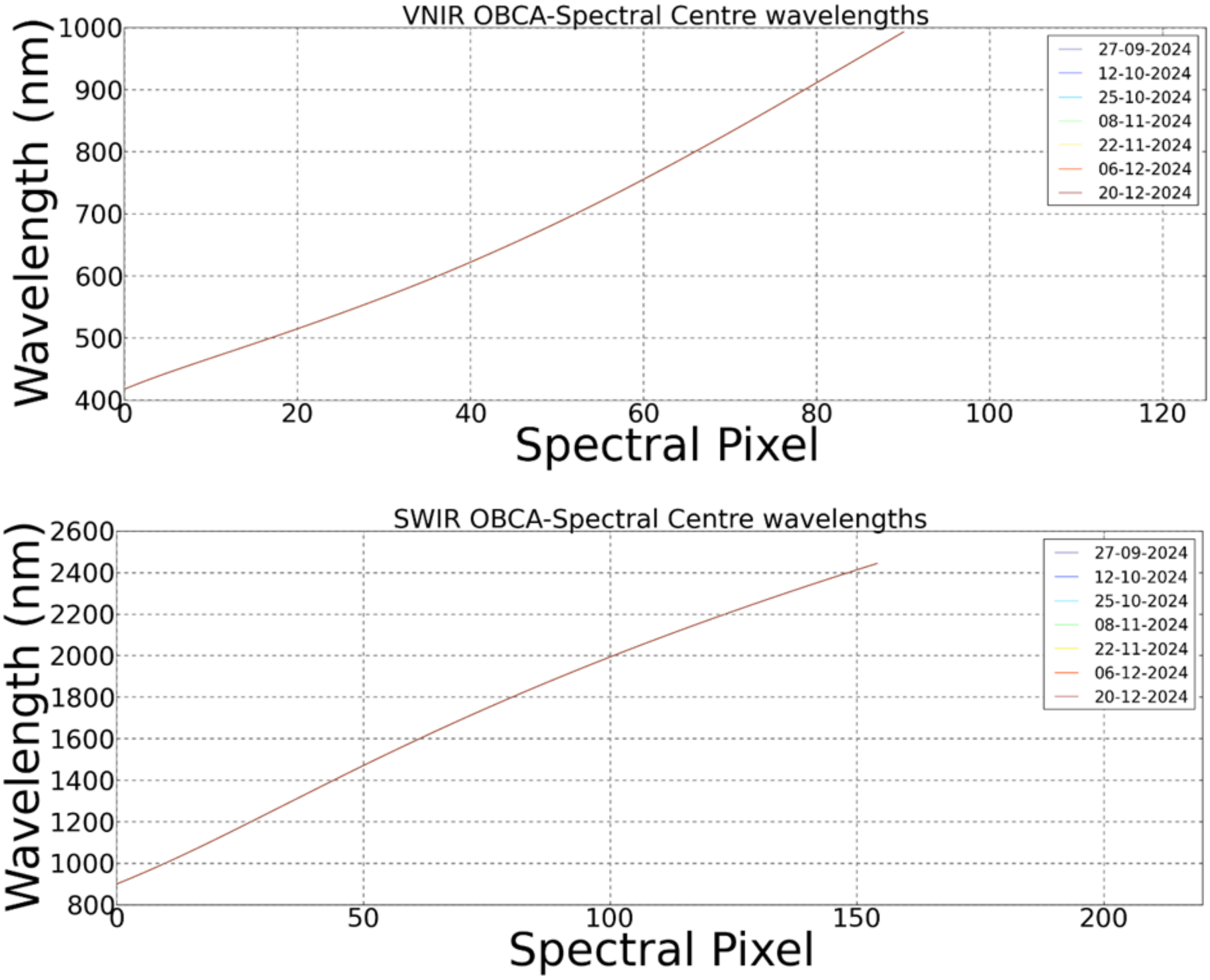


Figure 7-7 VNIR (top) and SWIR (bottom) center wavelength in nm

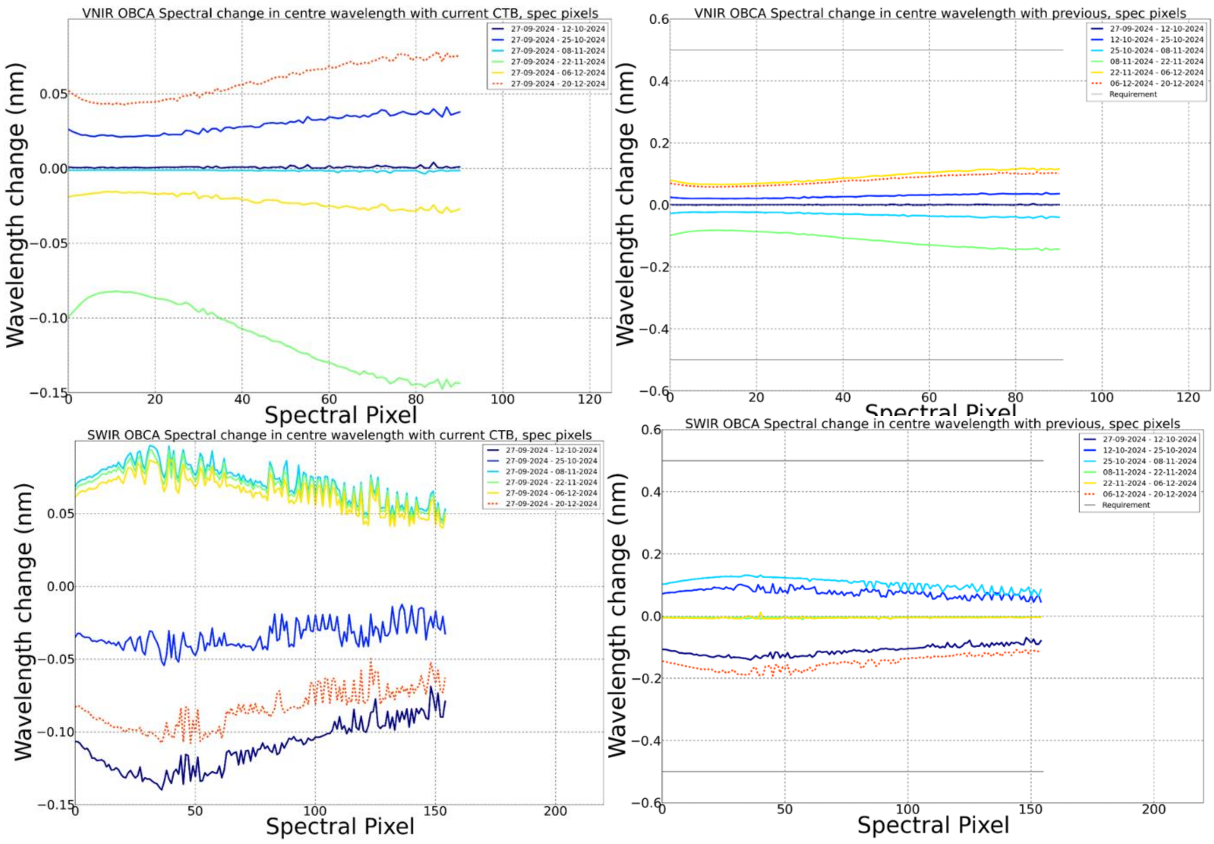
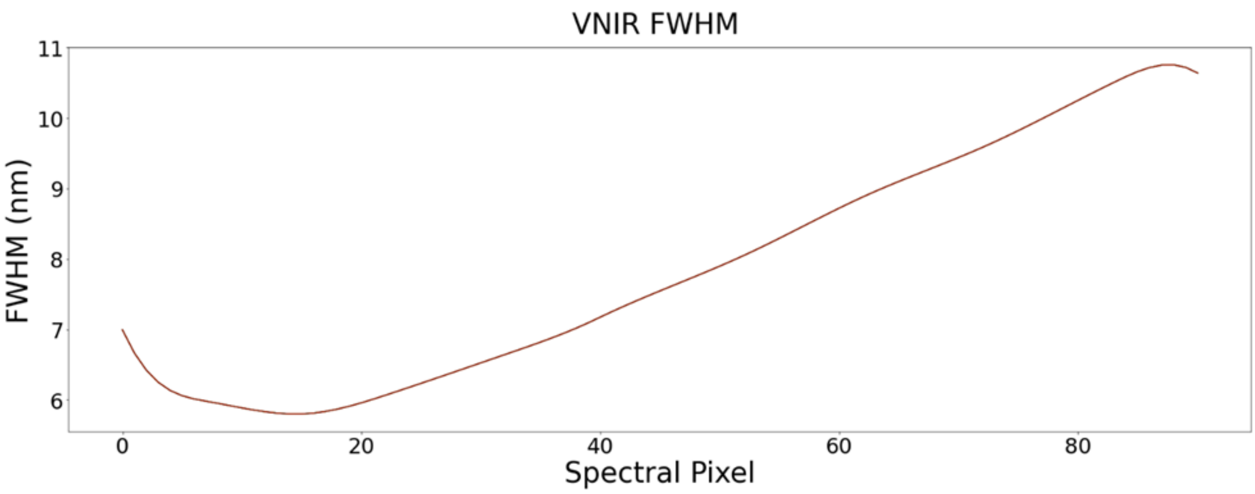


Figure 7-8 Change in center wavelength per spectral pixel for VNIR (top) and SWIR (bottom). Left panels show the changes with respect to current spectral calibration table in use and right panels with respect to the previous measurements.



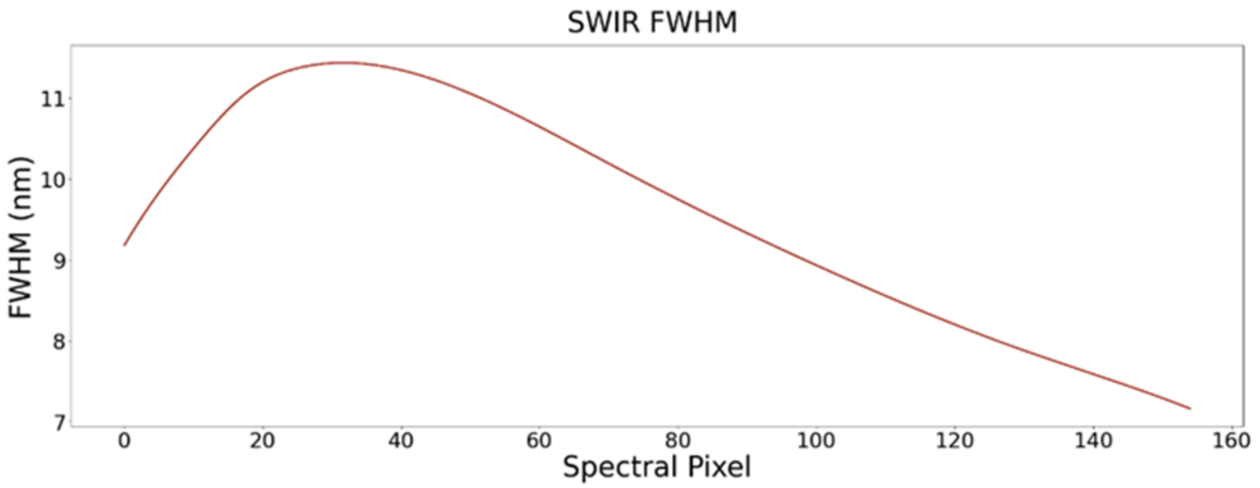


Figure 7-9 VNIR (top) and SWIR (bottom) FWHM in nm

CW and FWHM are available in the spectral calibration tables (see Table 7-7) and System Response Functions (SRF) per band are modelled by a Gaussian shape using those parameters.

No new calibration products were generated and delivered during the reporting period.

Product	Type	Date of Generation	Date of Validity Start	Date of Validity End	Delivered to

Table 7-7 Generated spectral calibration tables

7.5.3 Radiometric Calibration

Category	01.10.2024 to 31.12.2024	
	Number of Archived Observations	Size (in GB)
Total	19	84.7
Deep Space	4	5.2
Rel. Radiometric	11	42.9
Abs. Radiometric	2	2.6
Linearity	2	34

Table 7-8 Number and size of archived radiometric calibration observations

The radiometric properties – characterized in particular by the calibration coefficient for each band (spectral coordinate) and pixel (spatial coordinate) and radiance – during this reporting period are investigated, considering all bands and pixels and radiances provided in Level 1B, Level 1C and Level 2A products.

Radiometric calibration coefficients (see Figure 7-10, Figure 7-11 and Table 7-9) and VNIR RNU (response non-uniformity, see Figure 7-13) were affected by the degradation of the VNIR sensor during commissioning but have stabilized from Q1 2023. In-flight, the gain matching coefficients (see Figure 7-12), the SWIR calibration coefficients, and the SWIR RNU (response non-uniformity, see Figure 7-13) have been stable.

During the reporting period, 2 Absolute Radiometric calibration measurements were obtained. This took place on: 17.11.2024 and 06.12.2024.

Albeit now relatively small in magnitude, changes in the VNIR sensor have led to the creation of new calibration and reference tables for the new absolute radiometric measurement.

Although the VNIR degradation has almost stopped, the overall effects are visible in the reference measurements of the sun. However geometric conditions (sun-earth distance, pointing angle) also play a role in the absolute magnitude so the degradation cannot be quantified with these reference measurements.

The major conclusions of the monitoring of the absolute performance is summarized as follows:

- Changes in the VNIR sensor have affected the absolute Radiometric calibration coefficients: the increasing signal in the VNIR sensor, although not homogeneous, has resulted in decreasing radiometric coefficients. In this reporting period, the calibration coefficients decreased by about -0.30% to offset the increase in absolute (Figure 7-10 and Figure 7-11). Regarding RNU, the degradation features are still visible in the focal plane (Figure 7-13). Lastly, the Gain Matching correction has been relatively stable during this reporting period (Figure 7-12).

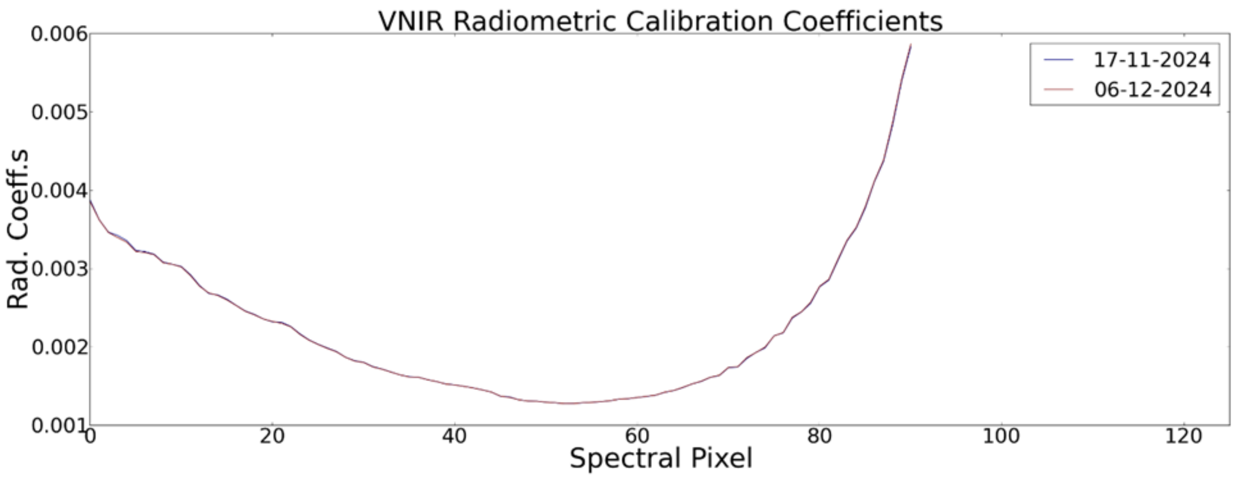
- The SWIR sensor has shown good stability during this reporting period, with no significant changes in the gain matching, RNU or radiometric calibration coefficients (Figure 7-10 and Figure 7-11).

- Regarding the total change in calibration corrections as a result of the VNIR degradation, almost all pixels experienced a change of less than 2.5% between consecutive measurements as set in requirement [HSI-POSR-0410]. The only pixels which exceeded this value were already marked as dead during inflight assessment. No SWIR pixels experienced a change of more than 2.5% between consecutive absolute calibration measurements.

- New VNIR and SWIR calibration and reference tables were created for both absolute radiometric measurements, mainly due to the changes in the VNIR sensor. The VNIR radiometric calibration coefficients have decreased in this reporting period to offset the increasing VNIR signal. The changes are small, and within requirements, so the dynamic coefficients are not calculated and calibration coefficients are taken directly from the most recent calibration table as envisioned at the beginning of the mission.

- Originally, only one calibration for 17.11.2024 was scheduled for this quarter but after some anomalous results in the change in radiometric coefficients and fringing pattern, a second one was scheduled for 06.12.2024. The November acquisition occurred during the four-day period with slightly increased internal temperatures (attributed to a check with the second gyroscope powered during that period). The December acquisition came after this period and is more in line with expectations based on the behavior of the VNIR sensor. The SWIR sensor was unaffected

- Since April 2024, Absolute Radiometric calibration measurements are made at intervals of two months, following the stable performance of both sensors, and to allow for the extension of the lifetime of the solar diffuser. An extra calibration request was made due to the anomaly in November, hence the deviation from the bimonthly plan.



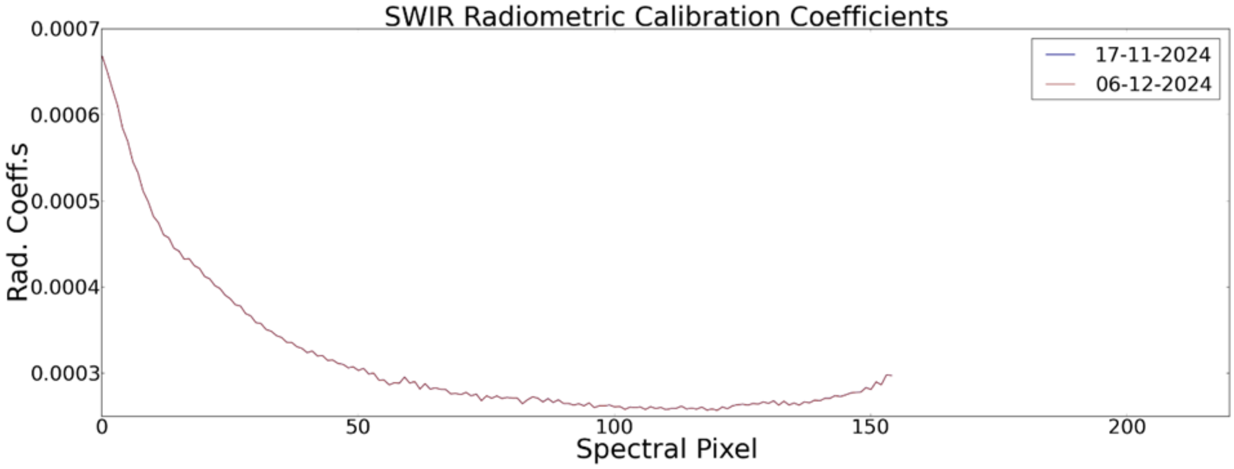


Figure 7-10 VNIR (top) and SWIR (bottom) calibration coefficient in mW/cm²/sr/µm

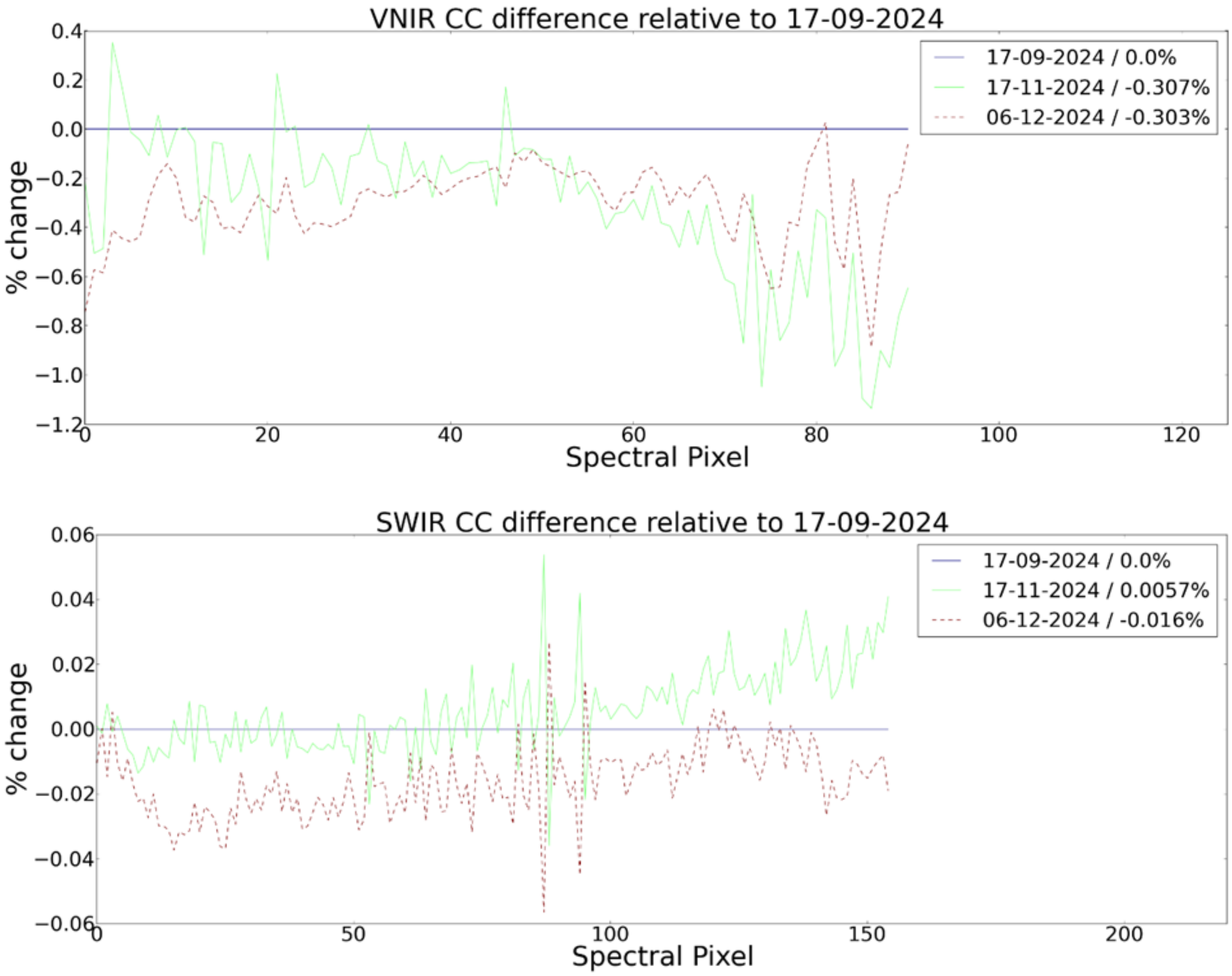


Figure 7-11 Percentage change in VNIR Calibration Coefficients (top) and SWIR Calibration Coefficients (bottom)

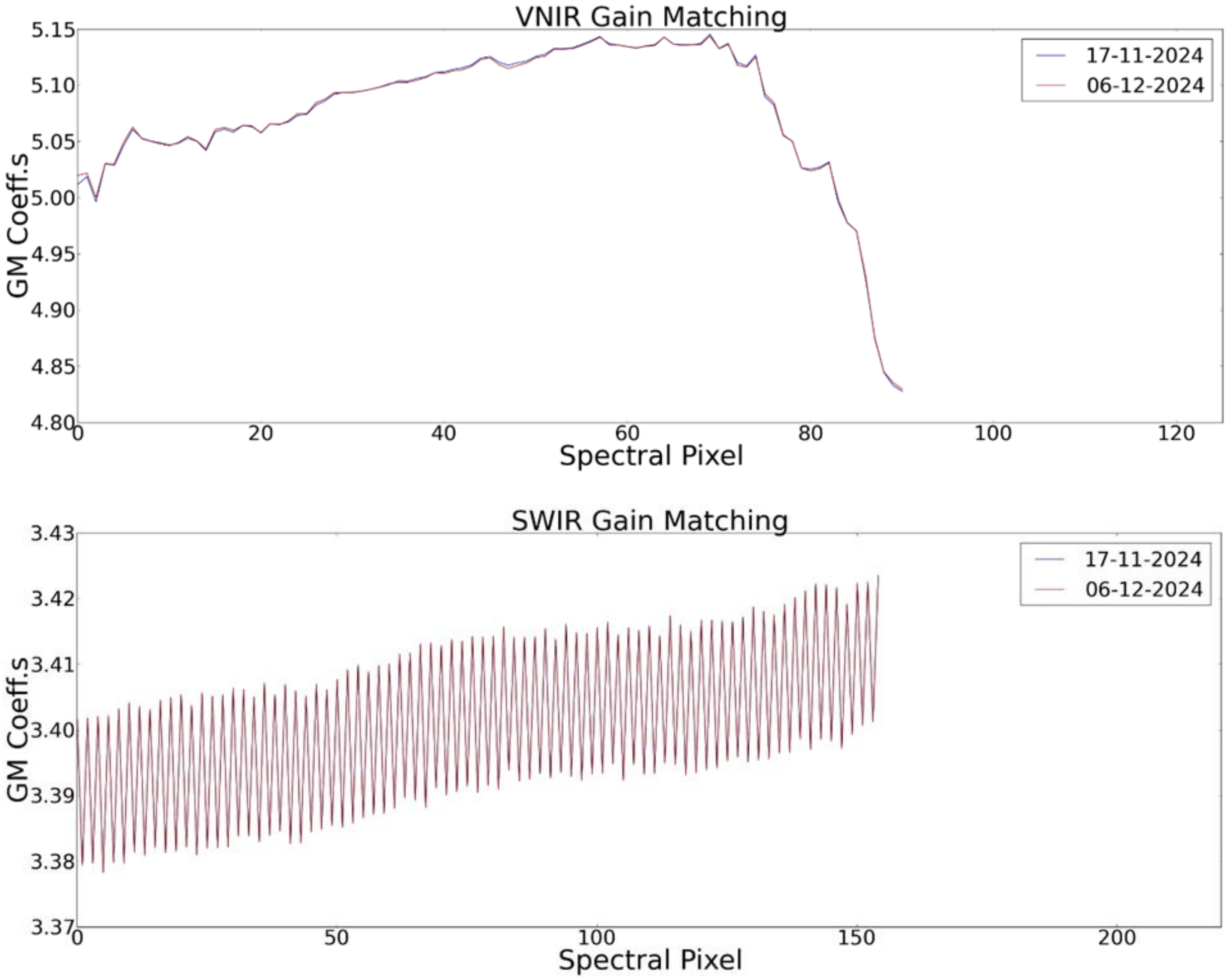
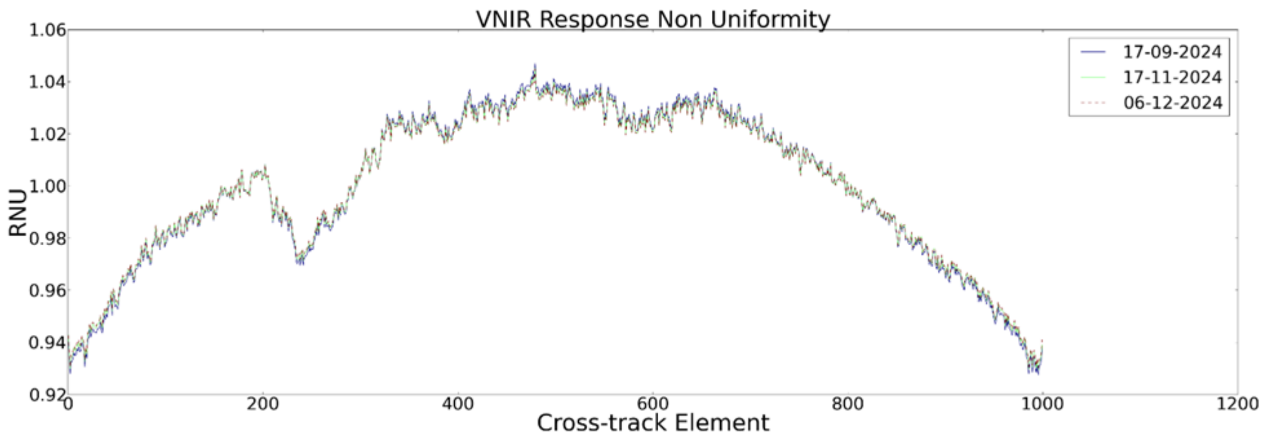


Figure 7-12 VNIR (top) and SWIR (bottom) gain matching calibration coefficients



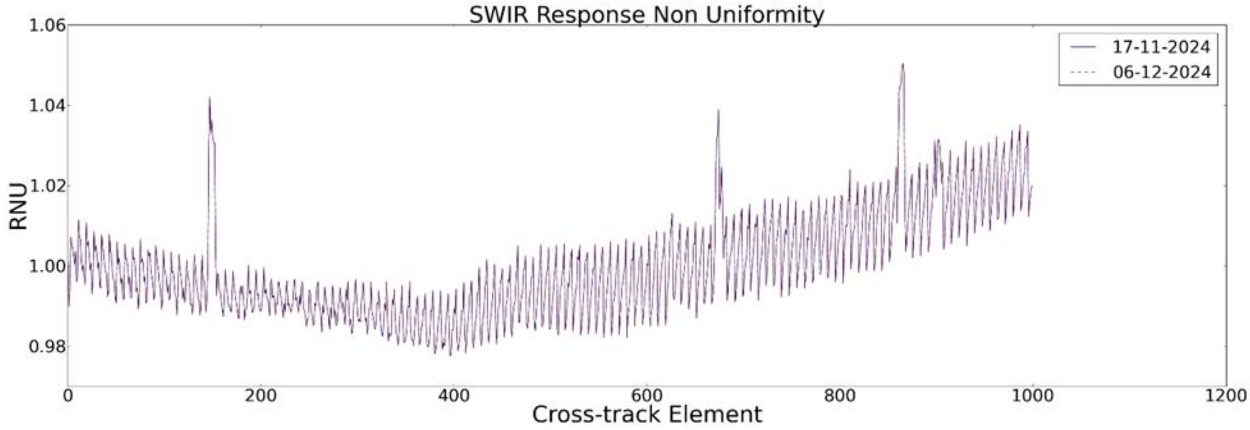


Figure 7-13 VNIR (top) and SWIR (bottom) response non-uniformity coefficients

Signal-to-Noise Ratio

The Signal-to-Noise Ratio (SNR) is derived from the Linearity reference measurements. This is not a perfect set-up for the assessment of the SNR as the linearity measurements only cover a single wavelength and light level at increasing integration times. However, it is well constrained, covering a wide range of radiances including the levels of the reference radiance spectrum that is used to evaluate the requirements (30% reflectance, 30° sun incidence angle, 21 km visibility, target 500 m above sea level). The lamp reference measurements are not used, as the reference spectrum is not well covered at the radiances of the lamp and extrapolation would be required to test the performance at the SNR requirements. Those requirements are: SNR greater than 500 at 495 nm in VNIR for the reference spectrum value given a 10 nm pixel; and SNR greater than 150 at 2200 nm in SWIR for the reference spectrum given a 10 nm pixel.

For the VNIR sensor, SNR is computed from the linearity calibration measurement. SNR values are shown as a contour map with the reference radiance spectrum as a blue line. Contour lines with SNR values of 150 and 500 are also shown in black. The plot in low gain mode includes the mission requirement which is evaluated at 495 nm for a radiance value of 36 mW/cm^2/μm/sr and is expected to be greater than 500: the calculated value here is 592. The radiance value used here for the evaluation is the value at 495 nm of the reference radiance spectrum after bandwidth normalization to a 10 nm pixel (see Figure 7-15).

For the SWIR sensor, SNR is also computed from the linearity calibration measurement. SNR values for the high gain mode are shown as a contour map with the reference radiance spectrum as a blue line. Contour lines with SNR values of 150 and 500 are also shown in black. The plot in high gain mode includes the mission requirement which is evaluated at 2200 nm for a radiance value of 0.5 mW/cm^2/μm/sr and is expected to be greater than 150: the calculated value here is 199. The radiance value used here for the evaluation is the value at 2200 nm of the reference radiance spectrum after bandwidth normalization to a 10 nm pixel (see Figure 7-16).

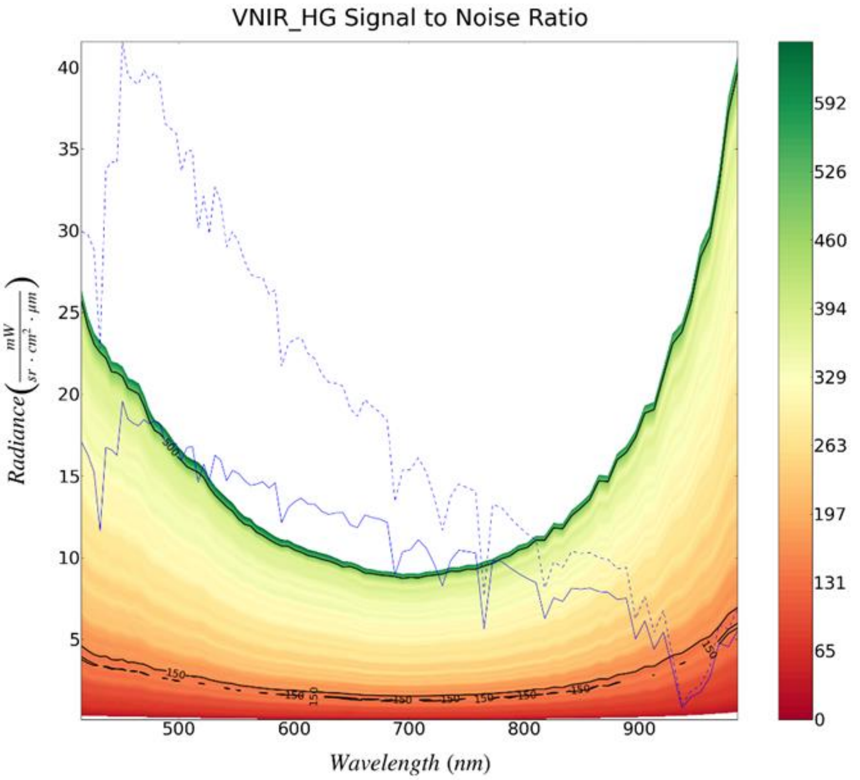


Figure 7-14 SNR contour map for VNIR high gain from the LED linearity observations observed on 07.11.2024.The reference radiance is shown with a blue line and after bandwidth normalization to a 10 nm pixel (dotted). Contour lines with SNR values of 150 and 500 are also shown in black.

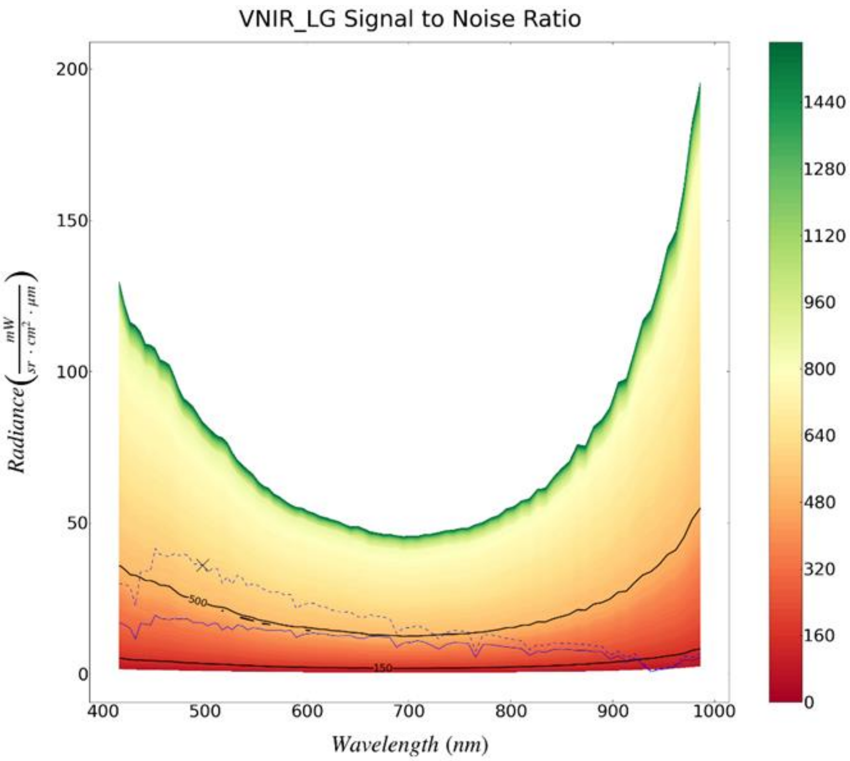


Figure 7-15 SNR contour map for VNIR low gain from the LED linearity observations observed on 07.11.2024. The reference radiance is shown with a blue line and after bandwidth normalization to a 10 nm pixel (dotted). Contour lines with

SNR values of 150 and 500 are also shown in black. The mission requirement is evaluated at 495 nm for a radiance value of 36 mW/cm²/µm/sr (marked with a black cross) and is expected to be greater than 500.

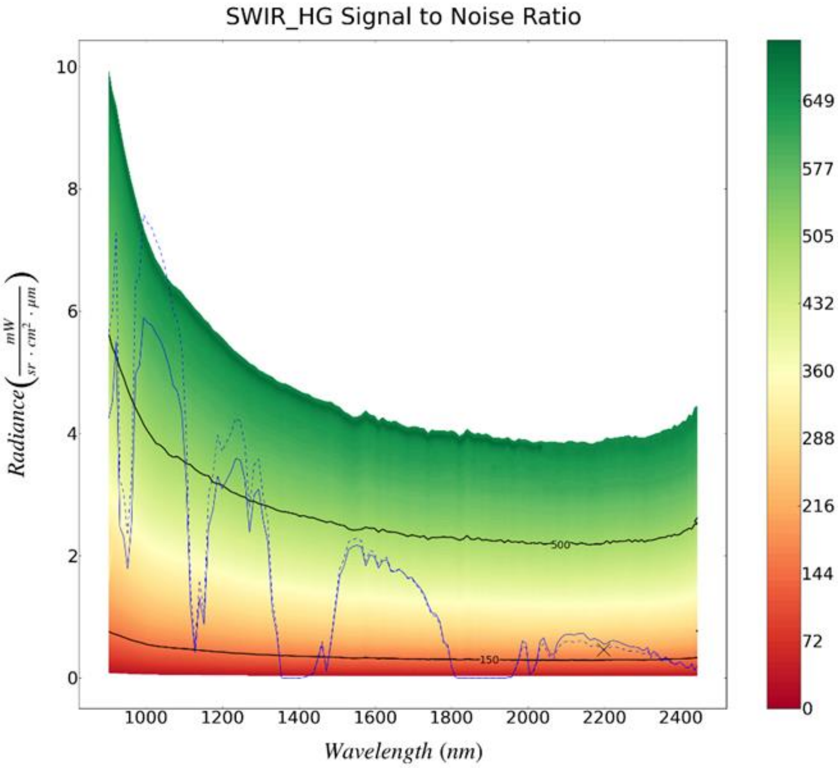


Figure 7-16 SNR contour map for SWIR high gain from the LED linearity observations observed on 07.11.2024. The reference radiance is shown with a blue line and after bandwidth normalization to a 10 nm pixel (dotted). Contour lines with SNR values of 150 and 500 are also shown in black. The mission requirement is evaluated at 2200 nm for a radiance value of 0.5 mW/cm²/µm/sr (marked with a black cross) and is expected to be greater than 150.

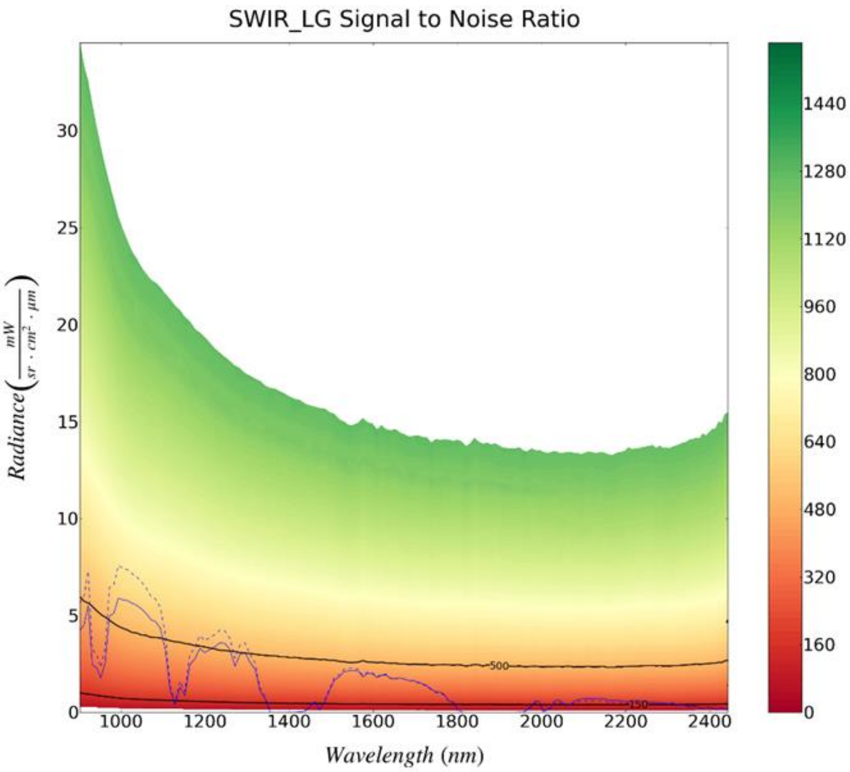


Figure 7-17 SNR contour map for SWIR low gain from the LED linearity observations observed on 07.11.2024.The reference radiance is shown with a blue line and after bandwidth normalization to a 10 nm pixel (dotted). Contour lines with SNR values of 150 and 500 are also shown in black.

The following calibration products were generated and delivered:

Product	Type	Date of Generation	Date of Validity Start	Date of Validity End	Delivered to
ENMAP01-CTB_RAD-20241218T000000Z_V040100_20241209T080856Z	CTB_RAD	09.12.2024	18.12.2023	-	DIMS
ENMAP01-REF_SUN-20241218T000000Z_V040100_20241209T080856Z	REF_SUN	09.12.2024	18.12.2023	-	DIMS

Table 7-9 Generated radiometric calibration tables

7.5.4 Geometric Calibration

There have been no new geometric calibration tables generated in the reporting period.

Type of Calibration Table	ID of Calibration Table	Date of Generation	Date of Validity Start	Date of Validity End
None				

Table 7-10 Generated new geometric calibration tables

The performance of the geometric calibration table is assessed in chapter 7.6.3.

7.6 Internal Quality Control

7.6.1 Archive

Within the given time period (01.10.2024 to 31.12.2024), 1819 datatakes with a total of 17288 tiles were acquired and archived (remark: additional datatakes acquired during this period but for which the archiving is pending might be missing in the statistics).

The overall quality rating statistics are listed in Table 7-11, and in relation to the Solar Zenith Angle (SZA) in Table 7-12. Also these ratings are further detailed for the VNIR and SWIR detector in Table 7-13, showing a nominal performance rating for the given quality thresholds.

In addition, the rating for the atmospheric conditions for the scenes are depicted in Table 7-14. When setting the atmospheric quality rating in relation to the illumination conditions (i.e., large SZA) during data acquisition (Table 7-15), 11% of the “reduced quality” ratings and 12% of the “low quality” ratings can be related to low Sun angles / night time acquisitions. In addition, the “low qualityAtmosphere” rating can be further related to high cloud cover (51% of the low qualityAtmosphere tiles) and the unavailability of enough DDV pixels (65%) (see Table 7-16). Consequently, the rating is absolutely reasonable and can be explained.

Parameter	Value	Percentage	Number of tiles
overallQuality	Nominal	99,5%	17795
	Reduced	<1%	23
	Low	<1%	76

Table 7-11 Overall quality rating statistics

Parameter	Number of tiles	Sub-Parameter	Number of tiles

overallQuality = Low	76		
		Thereof with SZA > 70°	76

Table 7-12 Overall quality rating in relation to Sun Zenith Angle (SZA)

Parameter	Number of tiles	Sub-Parameter	Number of tiles
overallQuality = Reduced	23		
		Thereof with qualityVNIR nominal	1
		Thereof with qualitySWIR nominal	22
overallQuality = Low	76		
		Thereof with qualityVNIR nominal or reduced	23
		Thereof with qualitySWIR nominal or reduced	69

Table 7-13 Reduced and low quality rating statistics

Parameter	Value	Percentage
QualityAtmosphere	Nominal	35%
	Reduced	17%
	Low	48%

Table 7-14 QualityAtmosphere rating statistics

Parameter	Number of tiles	Sub-Parameter	Number of tiles
overallAtmosphere = Reduced	3122		
		Thereof with SZA > 60°	1103
		Thereof with SZA > 70°	201
		Thereof with SZA > 80°	36
overallAtmosphere = Low	8585		
		Thereof with SZA > 60°	3119
		Thereof with SZA > 70°	1180
		Thereof with SZA > 80°	277

Table 7-15 QualityAtmosphere rating in realtion to Sun Zenith Angle (SZA)

Parameter	Number of tiles	Sub-Parameter	Number of tiles
overallAtmosphere = Low	8585		
		Thereof with Cloud Cover > 66%	5011
		Thereof with DDV warnings	6768

Table 7-16 QualityAtmosphere rating in relation to Cloud Cover and DDV availability

Remark about definition of EnMAP low quality collection

The quality rating of EnMAP products is based on image parameters, such as illumination conditions (i.e., sun elevation angle) and image defects, and on possible anomalies in the image data or instrument telemetry. These parameters are retrieved during the pre-processing and are added to the metadata and quality layers for every archived L0 product. In EOWEB GeoPortal two collections of EnMAP L0 products are available: “EnMAP-HSI (L0)” and “EnMAP-HSI (L0), Low Quality”. An L0 product is assigned to the low-quality collection if the corresponding metadata item qualityFlags.overallQuality is equal to 2 (low quality). This happens for products with a significant number of striping, saturation, artefact or dead pixels, when the screening of data and instrument indicates non-nominal behavior or, in the majority of cases, when the sun elevation angle is less than or equal to 0 (e.g., night scenes). A detailed definition of qualityFlags. overallQuality is given in Sec. 4.4.9 in the L1B ATBD (EN-PCV-TN-4006).

7.6.2 Level 1B

7.6.2.1 Radiometric Performance

Defective / de-calibrated detector elements

Using the Detector Map components, an offline check of possibly defective or de-calibrated detector elements is conducted. In particular, a detector element is identified as “possibly defective” if it is suspicious in at least 75% of the useful tiles. Note that this analysis is based on L1B_RAD data, so no dead / defective pixel interpolation was carried out. Within the given reporting period, the following indications for defective pixels are found for the VNIR and the SWIR camera:

VNIR (total of 17894 tiles, with 17821 suitable for analysis):

Newly found suspicious pixels in green, previously detected in **black**, no longer present ones in ~~red~~.

Band	Cross-track element
~~77~~	~~600~~
85	14
89	395

Note that the band index starts at 1.

SWIR (total of 16380 tiles, with 16101 suitable for analysis):

Newly found suspicious pixels in green, previously detected in **black**, no longer present ones in ~~red~~.

Band	Cross-track element	Band	Cross-track element	Band	Cross-track element
2	235, 286, 593, 673	48	511	96	341, 819
3	381	50	311, 344, 395	101	318
4	362, 363, 418	53	97, 98	106	107
5	687	54	~~602~~, 941	107	~~265~~, 764
7	910	56	221, 965	108	886
8	801	58	632, 922	111	315
9	124	59	89, 90	118	837
11	715	61	312		
14	29, 684	63	123		
16	535	69	864		
28	104	72	801, 844, 845		
29	855, 928	75	737		
30	360, 855	85	525		
31	360	91	973		
33	560	92	677, 973		
38	241				

39 486

Dead detector elements

Within the given reporting period, the statistics for dead pixels are provided in Table 7-17 and Table 7-18. When comparing these numbers to the estimates in Ch. 7.5.1, one must bear in mind that the latter is based on the full detector readout configuration, while the numbers provided in the following are related to the standard readout configuration as provided in the user product. Because of the smaller readout area, these following dead pixel numbers are lower in comparison.

Parameter	Number of dead pixels	Percentage of tiles in reporting period
DeadPixelsVNIR	137	100%

Table 7-17 Dead pixel statistics, VNIR

Parameter	Number of dead pixels	Percentage of tiles in reporting period
DeadPixelsSWIR	1509	100%

Table 7-18 Dead pixel statistics, SWIR

Saturation and radiance levels

Within the given reporting period, no indications for increased saturation defects are found for the VNIR and the SWIR camera (see Table 7-19 and Table 7-20).

Parameter	Value (per mille of scene)	Percentage of tiles
SaturationCrosstalkVNIR	0	94%
	> 0 per mille	5.6%
	> 10 per mille	1.5%

Table 7-19 Saturation statistics, VNIR

Parameter	Value (per mille of scene)	Percentage of tiles
SaturationCrosstalkSWIR	0	95%
	> 0 per mille	6.4%
	> 10 per mille	0.2%

Table 7-20 Saturation statistics, SWIR

Other radiometric artifacts

Within the given reporting period, the striping performance is similar to the one encountered during the Commissioning Phase. Within PCV, different de-striping approaches were tested, and the selected one by M. Brell (GFZ) is implemented in processor version V01.02.00 (07.03.2023).

Apart from this, no indications for an increase in general radiometric artifacts are found for the VNIR and the SWIR camera (see following tables).

Parameter	Value (number of pix)	Percentage of tiles
generalArtifactsVNIR	0	0%
	> 0	100%
	> 10	4.9%
	> 100	0.6%
	> 1000	0%

Table 7-21 Artifacts statistics (without striping), VNIR

Parameter	Value (number of pix)	Percentage of tiles
generalArtifactsSWIR	0	0%
	> 0	100%
	> 10	100%
	> 25	5.8%
	> 100	0.9%
	> 1000	0%

Table 7-22 Artifact statistics (without striping), SWIR

7.6.2.2 **Spectral Performance**

For the analysis of the spectral stability, the Detector Maps of all Earth datatakes acquired in the reporting period were used. Note that no smile correction was applied, so the analysis shows only on the instrument characteristics. At the wavelengths of stable atmospheric features (760 nm Oxygen absorption and CO2 absorption at ~2050 nm), simulations of spectral shifts were carried out by resampling the absorption in the interval of +/- 3.0 nm with steps of 0.05 nm. Then the signal of the Detector Maps and the simulated shifted absorptions were normalized, and a least-square fit was used where the sensed absorption matches the simulations. Also an additional polynomial fitting was applied, as especially the CO2 absorption band region has low signal an is thus significantly influenced by noise.

For the VNIR, when aggregating the shifts (Figure 7-18) the mean derivation is almost constant in across-track direction and -as before- around 0.5 nm towards shorter wavelengths, underpinning the consistency with the in-orbit spectral calibration and especially regarding the shape of the spectral smile. Note that of course these results are consistent within the limitations of this vicarious approach. Additionally, the variability of the vicariously estimated spectral calibration can be expressed as the standard deviation at 1 sigma is below 0.4 nm, which includes the spectral stability of EnMAP and as well the variations of the used Earth datatakes and the limitations of the method.

In summary, for the VNIR the estimated differences to the CTB_SPC consistent with the results of previous reporting periods, confirming the validity of the spectral calibration and the spectral stability of the instrument taking into accounts the limitations of the vicarious approach.

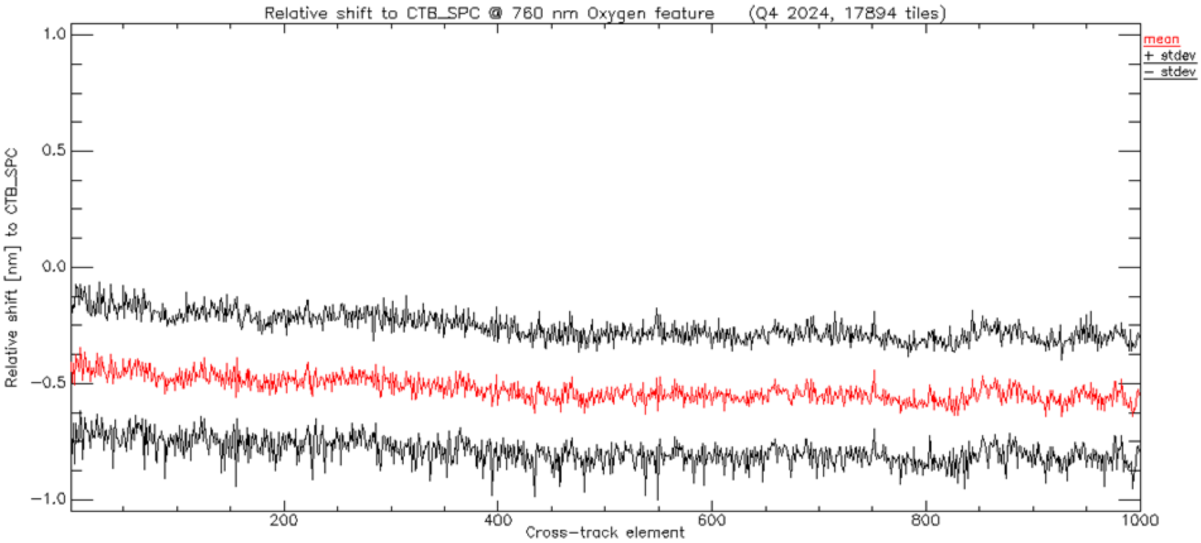


Figure 7-18 VNIR estimated spectral shift at 760 nm w.r.t the valid spectral calibration table (CTB_SPC), and relative spectral stability expressed at 1 sigma (Q4 2024, 17894 tiles)

For this analysis, the reference is thus not the nominal center wavelengths (i.e., a single number per band), but the CW per cross-track pixel, thus explicitly including the spectral smile (see Figure 7-19).

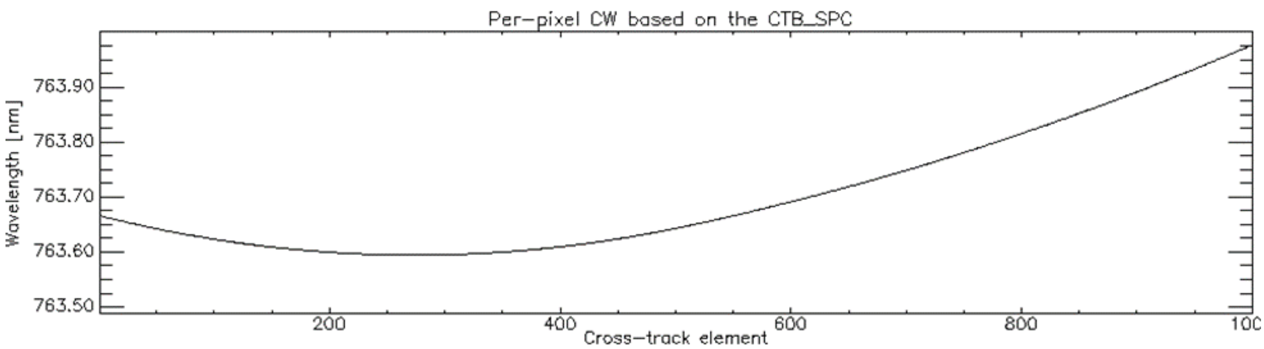


Figure 7-19 Center wavelengths per cross-track pixel based on the spectral calibration table (VNIR band 62) in the calibration table (CTB_SPC).

For the SWIR having less pronounced atmospheric absorption features, more influence of the background and a much lower signal level, the fitting also results in more clutter, as shown in Figure 7-20.

In order to demonstrate that the mean derivation to the CTB_SPC is within the spread of the data, the mean and standard deviation are calculated using the relative values, as shown in Figure 7-20. Here the differences to the CTB_ SPC (Figure 7-21) are well within 1 standard deviation, confirming the validity of the spectral calibration.

Considering the EnMAP bandwidths of ~8.5 nm (FWHM), the spread of the vast majority of successful fits is within 3 nm, which agrees with the estimated overall stdev of ~0.71 nm (1 sigma) shown in Figure 7-20. To conclude, also for the SWIR the spectral calibration and the instrument stability can be confirmed, and no significant changes to previous reporting periods were found.

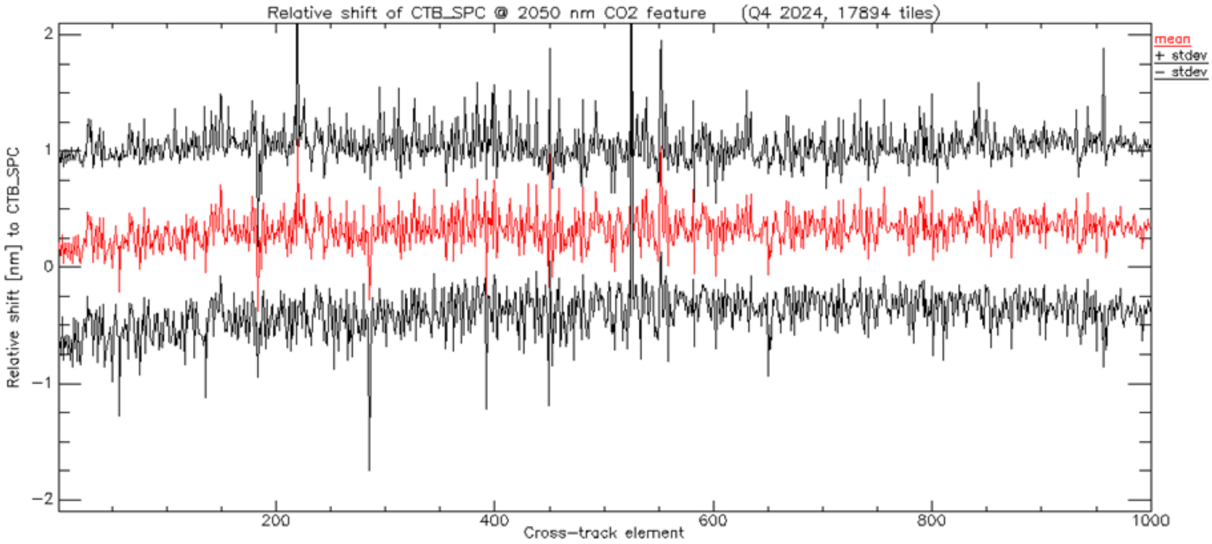


Figure 7-20 SWIR estimated spectral shift at 2050 nm w.r.t the valid spectral calibration table (CTB_SPC, shown below), and relative spectral stability expressed at 1 sigma (Q4 2024, 18226 tiles)

For this analysis, the reference is thus not the nominal center wavelengths (i.e., a single number per band), but the CW per cross-track pixel, thus explicitly including the spectral smile (see Figure 7-21).

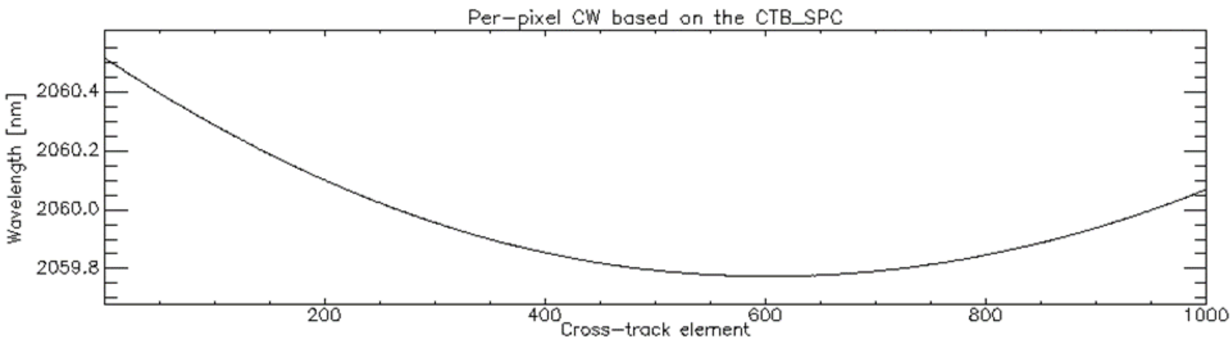


Figure 7-21 Center wavelengths per cross-track pixel based on the spectral calibration table (SWIR band 86).

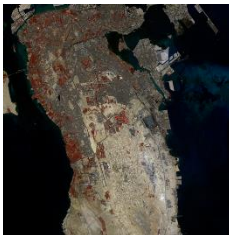
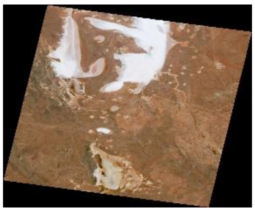
7.6.2.3 Routine check of scenes in context of updates in CTB_RAD, CTB_SPC calibration tables

7.6.2.3.1 CTB_RAD

In the context of routine checks after radiometric calibration update, Table 7-23 shows the summary.

Table 7-23 Validated CTB_RAD (from 09.12.2024)

Validated CTB	ENMAP01-CTB_RAD-20241218T000000Z_V040100_20241209T080856Z
Datatake used	ENMAP01-____L1B-DT0000085062_20240801T065323Z_012

	 Figure 7-22 Datatake used (Bahrain and Persian Gulf) ENMAP01-____L1B-DT0000105107_20241207T023754Z_002  Figure 7-23 Datatake used (Lake Lefroy, Astralia)
Summary of result	New CTB_RAD was confirmed. Larger changes in VNIR confirmed by CTB_RADs from 18.11.2024 and 9.12.2024, with 9.12.2024 is smoother and has less changes in the fringing, so usage of CTB_RAD from 9.12.2024 recommended by QC • VNIR: for both scenes, • relative changes to P32 are much higher than periods before by a factor of 1.5 to 2 • for given scene, the absolute change is between -0.001 and +0.05 and thus significantly higher as well • change is more prominent for high radiance targets (low gain) • for the given scene, VNIR fringing is prominent for many bands • Compared to CAL on 18.11., the change to P32 is now way smoother and spectrally flat, and fringing is less prominent • SWIR: for both scenes: • relative and absolute change to P32 are very small (below 0.055% for most bands), which is significant less than the change between P31 – P32 • for given scene, no SWIR fringing is visible

7.6.2.3.2 CTB_SPC

In the context of routine checks after spectral calibration update, Table 7-24 shows the summary.

Table 7-24 Validated CTB_SPC

Validated CTB	None
Datatake used	
Summary of result	

7.6.2.3.3 Checks for the development of potentially defective / de-calibrated detector elements over time

In the following, the QC analysis of potentially defective / de-calibrated detector elements is summarized for the full EnMAP in-orbit time from Q1, 2023 until Q4, 2024, followed by the analysis of all DMs using different sensitivity settings. By default, a pixel is considered as “potentially defective” if it is flagged in more than 75% of the Earth datatakes in the specified period; additionally, a more sensitive threshold of 50% was also used for this analysis. The database of suitable DetectorMaps is listed in Table 7-25.

Table 7-25 Numbers of suitable DetectorMaps (DMs) per quarter and in total

Period	**#VNIR**	**#SWIR**
2024 Q4	17821	17650
2024 Q3	17064	16938
2024 Q2	17911	17788
2024 Q1	16207	16106
2023 Q4	7286	7223
2023 Q3	10727	10677
2023 Q2	6303	6280
2023 Q1	2899	2973
All:	**96308**	**95635**

As can be seen from Table 7-26, there is a high temporal consistency for the VNIR sensor regarding potentially defective pixels when analyzing the Earth datatakes. Also increasing the sensitivity of the tests does not add many potential defective pixels.

Table 7-26 Detected potentially defective VNIR pixels using all DMs with a sensitive (50%) and normal (75%) threshold, as well as detected potentially defective pixels per quarter

	all DMs	all DMs	2023 Q1	2023 Q2	2023 Q3	2023 Q4	2024 Q1	2024 Q2	2024 Q3	2024 Q4
Threshold:	50%	75%	75%							
Band	**Cross-track element**									
2	129									
19	187		187				187			
76	600									
77	600	600	600		600				600	
85	14, 437	14	14	14	14	14	14	14	14	14
86	36, 368, 444									
89	395	395	395	395	395	395	395	395	395	395
91	36									

Similarly, also the potentially defective pixels in the SWIR (Table 7-27) did not change much over time using both the standard threshold and a more sensitive approach. As the SWIR band configuration did change in Q3 2023, also the band indices between 48 – 75 did change. For better readability, the band indices with the old configuration were mapped to the indices with the current band configuration in Table 7-27, also indicated by the yellow background.

Table 7-27 Detected potentially defective SWIR pixels using all DMs with a sensitive (50%) and normal (75%) threshold, as well as detected potentially defective pixels per quarter. Note that the SWIR band configuration did change for bands between 48 and 75 after Q3 2023, which is already accounted for in this table.

	all DMs	all DMs	2023 Q1	2023 Q2	2023 Q3	2023 Q4	2024 Q1	2024 Q2	2024 Q3	2024 Q4
Threshold:	50%	75%	75%							
Band	**Cross-track element**									
1	817					817	817			
2	235 286 593 673	235 286 593 673	235 286 593 673	235 286 593 673	235 286 593 673	235 286 593 673	235 286 593 673	235 286 593 673	235 286 593 673	235 286 593 673
3	381					381			381	381
4	362 363 418		362 363 418	362 363 418	362 363 418	362 363 418	362 363 418	362 363 418	362 363 418	362 363 418
5	687	687	687	687	687	687	687	687	687	687
7	472 910	910	910	910	910	910	910	910	910	910
8	801	801	801	801	801	801	801	801	801	801
9	124	124				124	124	124	124	124
11	715	715	715	715	715	715	715	715	715	715
14	29 684	29 684	29 684	29 684	29 684	29 684	29 684	29 684	29 684	29 684
16	535	535	535	535	535	535	535	535	535	535
19	84		84			84	84	84		
20			84			766				
28	104	104	104				104	104	104	104
29	855 928	855 928	855 928	855 928	855 928	855 928	855 928	855 928	855 928	855 928
30	360 855	360	360	360	360	360	360 855	360 855	360 855	360 855
31	360	360	360	360	360	360	360	360	360	360
33	560	560	560	560	560	560	560	560	560	560
38	241	241	241	241	241	241	241	241	241	241
39	486	486				486	486	486	486	486
48	511	511	511	511	511	511	511	511	511	511
49			218	218	218	218				
50	311 344 395	311 344 395	311 344 395	311 344 395	311 344 395	311 344 395	311 344 395	311 344 395	311 344 395	311 344 395
51	155		154 155	154 155	154 155	154 155	155			
53	97 98	97 98	97 98	97 98	97 98	97 98	97 98	97 98	97 98	97 98
54	602 941	602 941	602 941	602 941	602 941	941	602 941	602 941	602 941	941
56	221 965	221 965	221 965	221 965	221 965	221 965	221 965	221 965	221 965	221 965
58	632 922	632 922	632 922	632 922	632 922	632 922	632 922	632 922	632 922	632 922
59	89 90	89 90	89 90	89 90	89 90	89 90	89 90	89 90	89 90	89 90
61	312	312	312	312	312	312	312	312	312	312

63	123	123	123	123	123	123	123	123	123	123
66			93	93	93	93				
69	864	864				864	864	864	864	864
72	801 844 845	801 844 845	801 844 845	801 844 845	801 844 845	801 844 845	801 844 845	801 844 845	801 844 845	801 844 845
75	737	737			737		737	737	737	737
85	525	525	525	525	525	525	525	525	525	525
89	285		285	285	285					
91	973	973	973	973	973	973	973	973	973	973
92	677 973	677 973	677 973	677 973	677 973	677 973	677 973	677 973	677 973	677 973
96	341 819	341 819	341 819	341 819	341 819	341 819	341 819	341 819	341 819	341 819
100	513			513		513	513	513		
101	318	318	318	318	318	318	318	318	318	318
102			925	925	925					
106	107	107	107	107	107	107	107	107	107	107
107	265 764	764	265 764	764	764	265 764	265 764	265 764	265 764	764
108	886	886	886	886	886	886	886	886	886	886
111	315	315	315	315	315	315	315	315	315	315
118	837	837	837	837	837	837	837	837	837	837
128	350 357 882									

7.6.3 Level 1C

This report covers the timeframe from 01.10.2024 to 31.12.2024. No geometric calibration was performed during this period.

In the timeframe of this report, 1481 datatakes have been acquired. In 1082 of those datatakes (~73 %), enough ground control points (GCP) and independent check points (ICP) were found to perform a geometric accuracy assessment. The datatakes without enough GCPs were not assessed quantitatively, but a random subset of them was inspected visually. The vast majority of those datatakes was either almost fully covered with clouds or showing only water, desert or rain forest. The behavior is thus as expected.

The assessment of the RMSE values in the metadata is shown below in Figure 7-24.

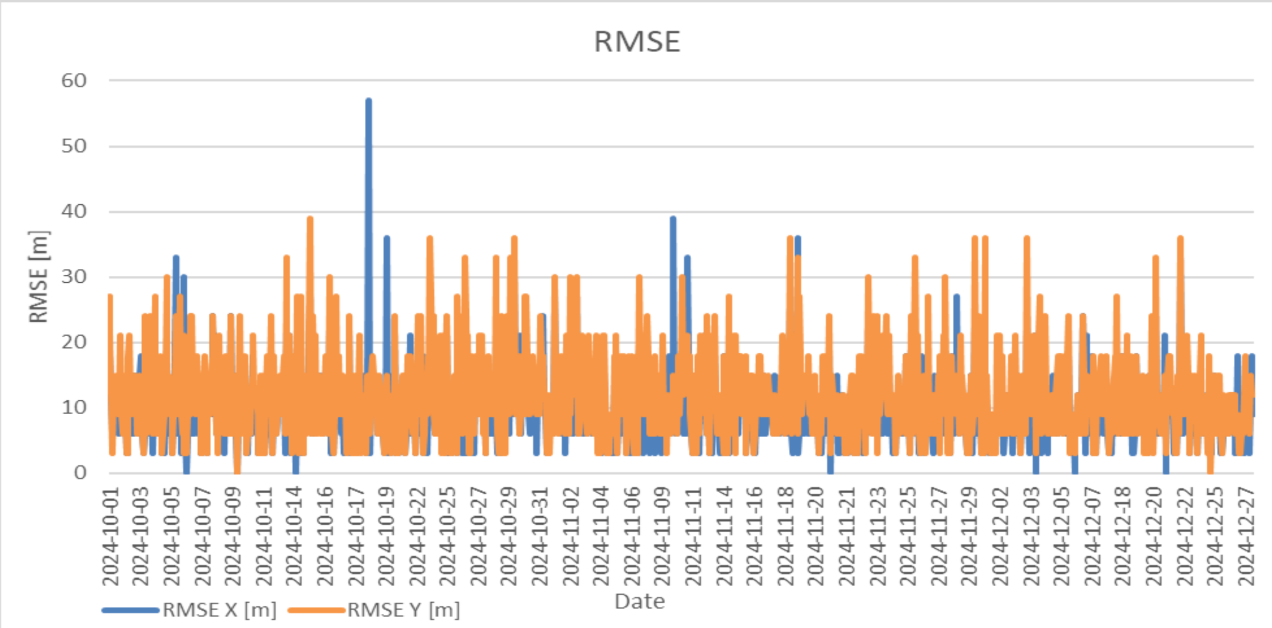


Figure 7-24 Assessment of RMSE values, calculated based on found ICPs, for all datatakes where ICP could be found

In x-direction, 7 datatakes (~0.6%) had an RMSE value above 30 m (1 GSD), whereas in y-direction, 15 datatakes (~1.4%) are above this threshold. For most of those datatakes, only very few GCP and ICP could be found during processing, making the results less reliable. The mean values are 9.32 m in x-direction and 11.94 m in y direction. This shows a very high geolocation accuracy for the datatakes where matching was possible. The requirement GRD-PCV-0155 (1 GSD) is thus fulfilled.

The average boresight angles, which can be interpreted as the correction and thus the error of the scene if no GCPs could have been found, correspond to approximately -20 m in x direction with a standard deviation of approximately 18 m and -30 m in y direction with a standard deviation of approximately 20 m on ground. It is reasonable to assume that the scenes where no GCPs could be found are in the same accuracy range and thus well within the requirement of 100 m (GRD-PCV-0150). Note that the x and y direction mentioned in this report are not in the image coordinate system but in UTM, as the evaluation is done on L1C products.

7.6.3.1 **Geometric accuracy**

EnMAP L1C products are matched against a reference image (Sentinel-2 data, if not stated otherwise) by using image matching techniques to assess the geometric accuracy. At the obtained checkpoints (CP), statistics are calculated to provide mean and RMSE values (Figure 7-25) for each scene. Note that the obtained accuracy in the analysis is always w.r.t. the reference image. This report covers EnMAP data from 01.10.2024 to 31.12.2024. A random sample of 524 L1C tiles was selected based on visual inspection of the catalogue quicklooks (e.g. to avoid cloudy images).

The requirement GRD-PCV-0155 shall be fulfilled:

The geolocation accuracy at nadir look direction of level 1C and 2A products shall be better than 1 GSD (1 sigma) in each direction with respect to reference images provided that reference images are available and sufficient similarity.

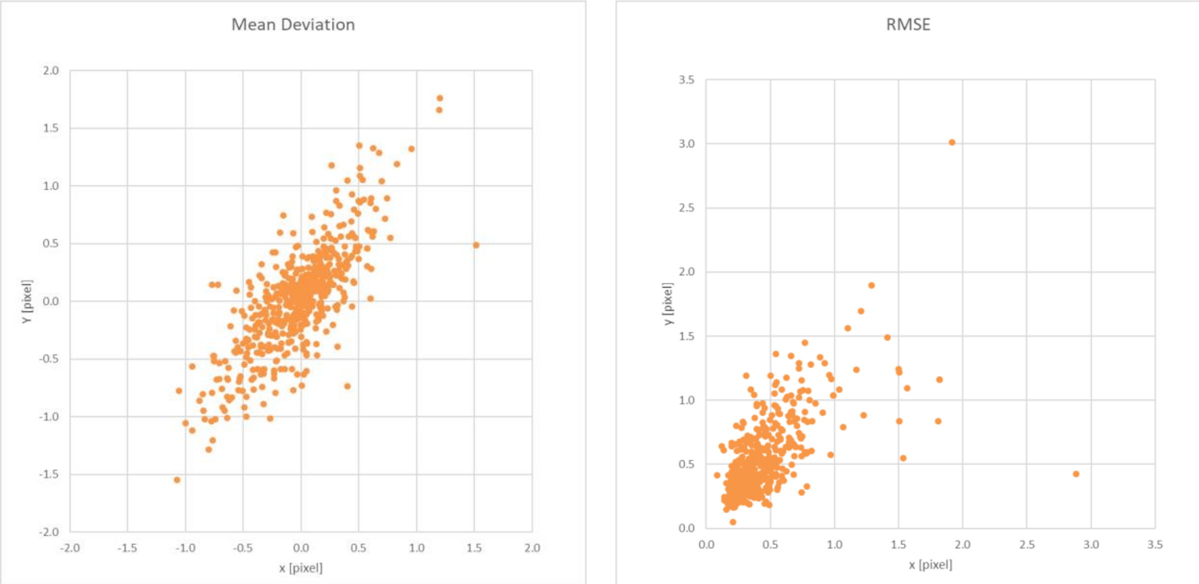


Figure 7-25 Mean deviation of EnMAP L1C products in pixel (left). RMSE value for EnMAP L1C products in pixel (right)

Note, that during processing the boresight angles and the geometric accuracy related quality flags are calculated on datatake level while in the figures and tables above, the accuracy is assessed per tile. The mean values over all 524 L1C tiles are -0.03 and 0.00 pixel in mean deviation with a standard deviation of 0.36 and 0.47 pixel while the mean RMSE values are 0.42 and 0.51 pixel, all in x and y direction respectively. The data show that for the vast majority of scenes the accuracy wrt. reference image is better than one pixel and thus the requirements are fulfilled. Compared to the last geometric QC report, the values are very stable (see Figure 7-27).

7.6.3.2 **Co-registration accuracy**

In this chapter, the co-registration accuracy is checked against the Space Segment requirement SRDS-PIM-0050 (EN-KT-RFW-003 is also to be considered here):

*The HS-Imager shall be designed such, that the geometric co-registration is ≤ 20 % of the nominal Ground Sampling Distance (0.2 * GSD linear displacement in both directions).*

For the assessment of co-registration accuracy, the SWIR data of EnMAP L1C products are matched against the corresponding VNIR data and the mean deviation values shown in this section (Figure 7-26).

This report covers EnMAP data from 01.10.2024 to 31.12.2024. A random sample of 524 L1C tiles was selected based on visual inspection of the catalogue quicklooks (e.g. to avoid cloudy images).

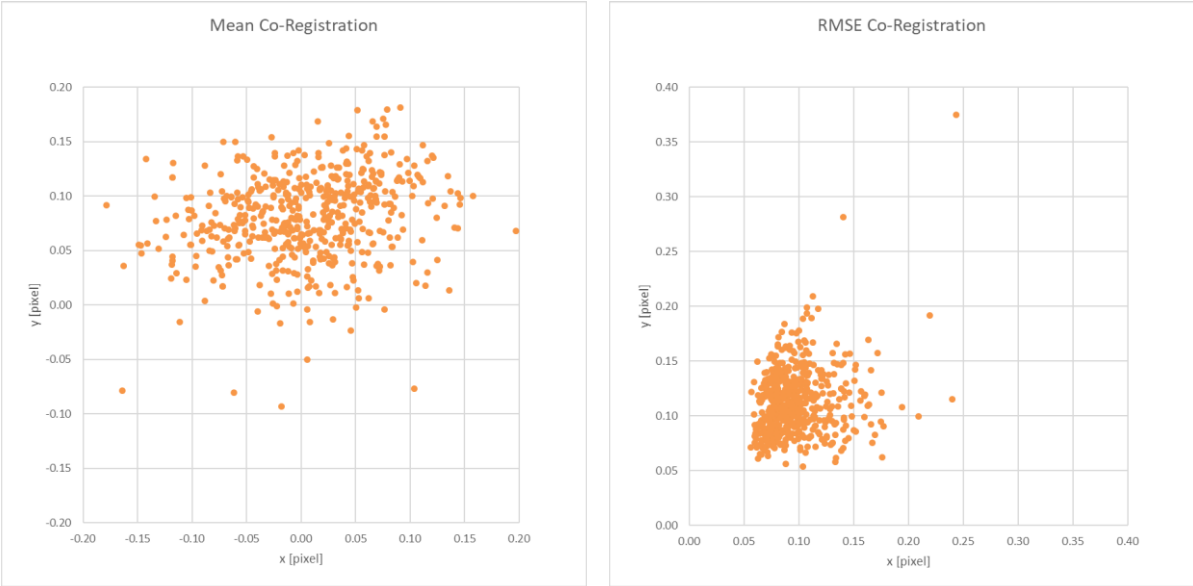


Figure 7-26 Mean deviation in pixel between VNIR and SWIR data of EnMAP L1C products (left). RMSE in pixel between VNIR and SWIR data of EnMAP L1C Products (right)

The data show, that the mean co-registration is well within the requirement. Note that the theoretical accuracy of the used matching algorithm is 0.1 pixel, and as can be seen in the RMSE values, still some mismatches were not removed by the blunder detection techniques that were applied. The mean deviation over all analyzed tiles are 0.01 pixel in x-direction with a standard deviation of 0.06 pixel and 0.08 pixel in y direction with a standard deviation of 0.04 pixel. Compared to the results in the previous geometric QC report, the values are very stable as can be seen in Figure 7-27.

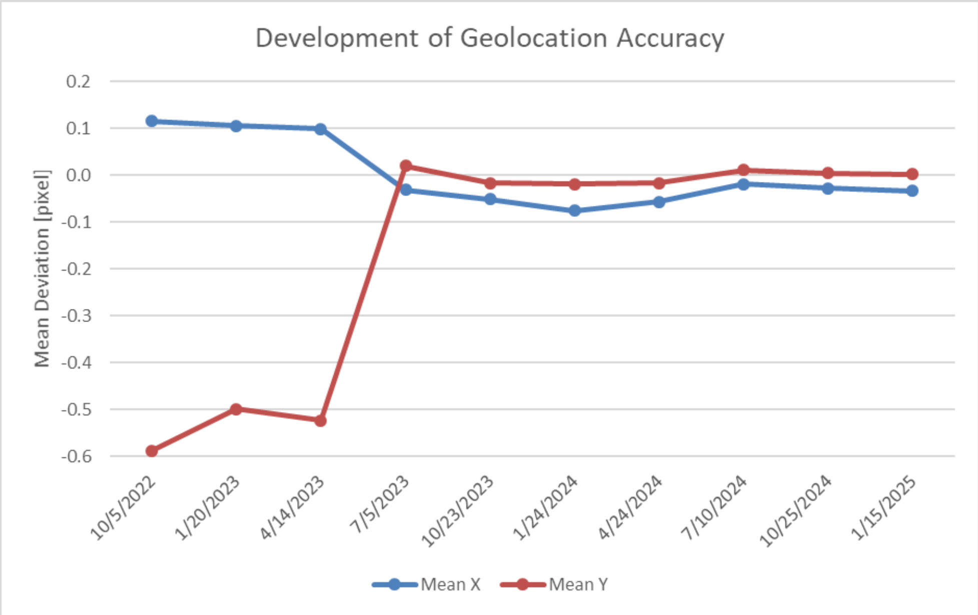
7.6.3.3 Development of geometric performance

Since the launch of EnMAP on April 1st 2022, the geometric performance has been improved significantly. This was achieved by different geometric calibrations and processor updates. Table 7-28 shows the measures performed, their date and their effect.

Date	Measure	Effect
01.08.2022	Fix of attitude processing	Improvement of absolute geolocation (w/o matching)
20.09.2022	Boresight Calibration	Improvement of absolute geolocation (w/o matching)
03.11.2022	1st Geometric Calibration	Improvement of absolute geolocation (w/o matching) Improvement of VNIR/SWIR co-registration (~0.8 pix -> ~0.4 pix)
11.02.2023	2nd Geometric Calibration	Improvement of VNIR/SWIR co-registration (~0.4 pix -> ~0.15 pix)
29.03.2023	Processor update (v01.02.00)	Improvement of VNIR/SWIR co-registration (~0.15 pix -> ~0.06 pix)
05.05.2023	Processor update (v01.03.01)	Improvement of geolocation accuracy

Table 7-28 Improvement of geometric performance

Figure 7-27 shows the development of the co-registration accuracy, measured as described in previous section. Again, after a significant improvement since commissioning phase, over the last report periods the accuracy has been very stable.



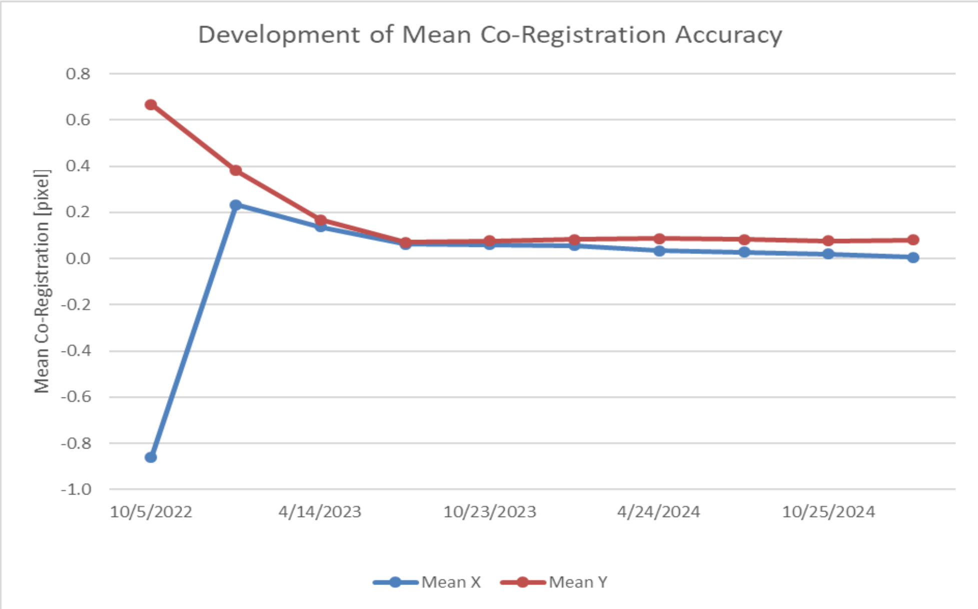


Figure 7-27 Development of co-registration accuracy based on the previous geometric QC reports

As most of the geometric processing – especially the matching against a reference image – is done on datatake level during L0 processing, the geometric accuracy and co-registration of data acquired earlier during the mission is not automatically improved when higher level products (L1B, L1C, L2A) are processed with the current processor version. However, during the currently ongoing L0 reprocessing of the whole archive, the geometric processing is executed with the latest processor version and geometric calibration table to make sure that the best geometric quality and co-registration is reached also for the reprocessed data. Users can recognize reprocessed data by checking the metadata tag **archivedVersion**: if the version is 01.03.00 or higher, then the geometric performance should be as analyzed in this report.

7.6.4 Level 2A

7.6.4.1 Validity of generated L2A "water" data

7.6.4.1.1 Analyzed scenes

The following scenes were taken into consideration:

DataTake - ID	Tile - ID	Location	L2A Option	Cirrus / Haze Removal	Overall Quality
102870	20	Whortonsville, USA	Water mode, water type “clear”	Cirrus	Nominal
103076	4	Hedge Reef, AUS	Water mode, water type “clear”	Cirrus	Nominal
103076	5	Cliff Islands, AUS	Water mode, water type “clear”	Cirrus	Nominal
103408	7	Oranjestad, AW	Water mode, water type “clear”	Cirrus	Nominal
104048	2	Torre Mileto, ITA	Water mode, water type “clear”	Cirrus	Nominal
104834	9	Wool Bay, AUS	Water mode, water type “clear”	Cirrus	Nominal
105644	10	Florida Keys, USA	Water mode, water type “clear”	Cirrus	Nominal
106830	3	Cervantes, AUS	Water mode, water type “clear”	Cirrus	Nominal

Table 7-29 Datatake IDs of analyzed water products

The below listed parameters were checked for above mentioned scenes by EOMAP:

Parameter	Check
Masking (Land, Water, Clouds, etc.)	No issues found.
Adjacency correction	No issues found.
Retrieval of atmospheric properties	No issues found.
Cirrus – correction	No issues found.
Retrieval of water leaving reflectance	No issues found.
Quality Mask	No issues found.

7.6.4.1.2 Data Checks

For the checks described in the following, the scene with the scene-ID 10307 and Tile Number 4 was selected. It is located at the Hedge Reef, Australia.

- Masking

First, the water mask is checked. The water body and the clouds, as well as shadows over land, are correctly masked (see Figure 7-28 and Figure 7-29). The very shallow parts were classified as geocoded background, and thus, won´t be processed afterwards.

Figure 7-28 Scene-ID 10307; RGB-Quicklook with Bands 611.02nm – 550.69nm – 463.73nm

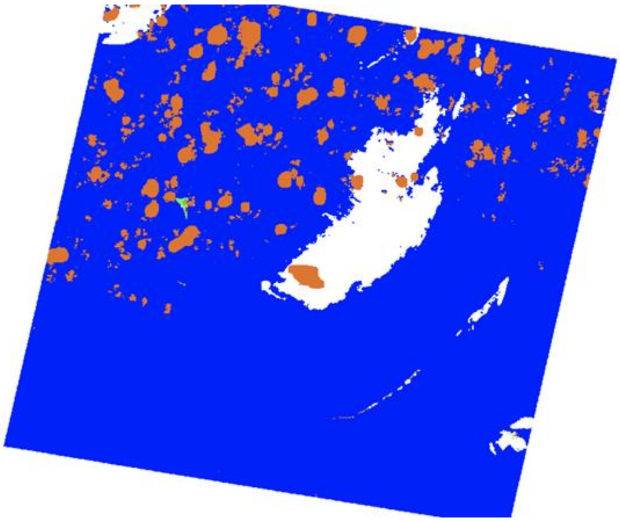


Figure 7-29 Scene-ID 10307; Geo Mask with No-Data in White, Water in blue, land in green and clouds in brown

- Adjacency Correction

Next, we check for the adjacency correction using the two sites ‘AC1’ and ‘AC2’ showed in .

Figure 7-30 Scene-ID 10307; RGB-Quicklook showing the sample locations with Bands 611.02nm – 550.69nm – 463.73nm

The coordinates of the sample locations are as follows:

AC 1: LAT -13.90686173 | LON 143.83554621

AC 2: LAT -13.88935100 | LON 143.82427698

For sampling, we choose two locations, one located over shallow water, the other over deep water (see Figure 7-30 for the sample locations).

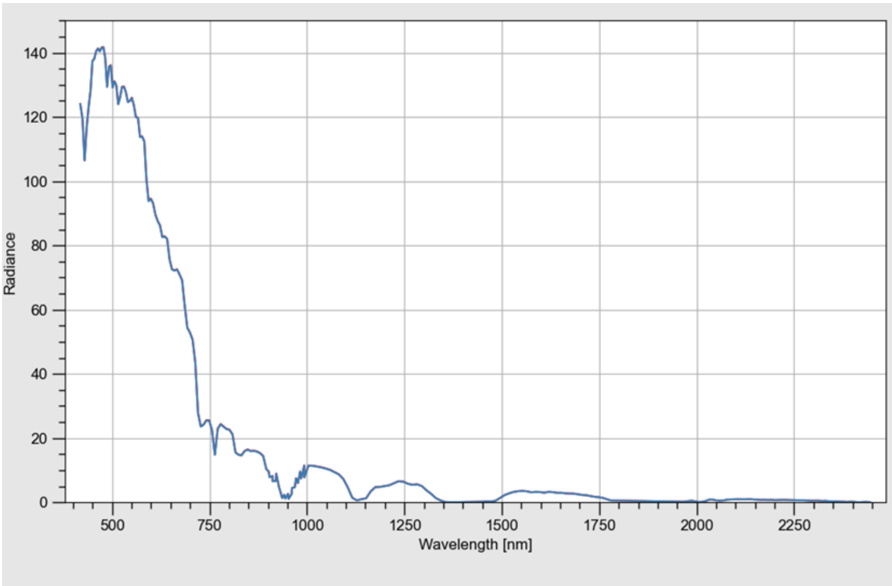


Figure 7-31 Scene-ID 86285; Signal sampled at location ‘AC 1’; red: measured signal, blue: corrected signal

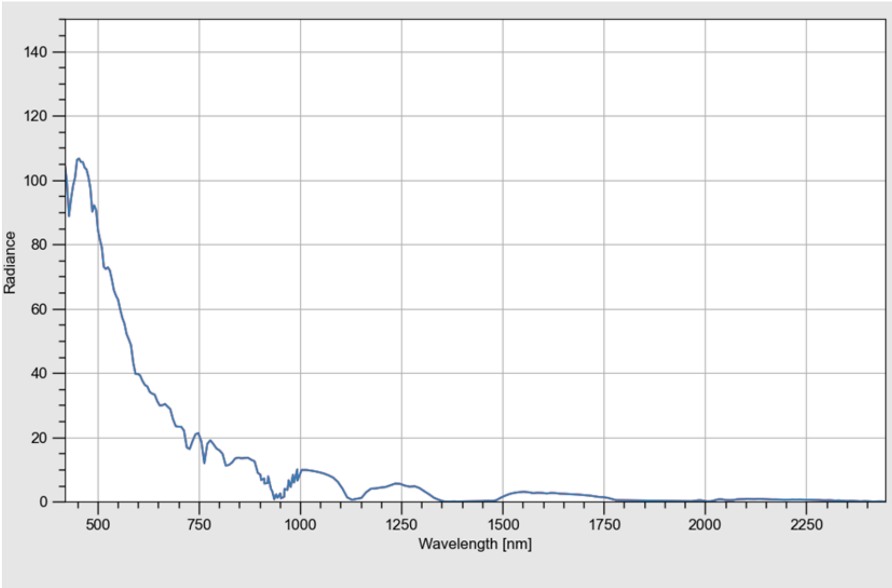


Figure 7-32 Scene-ID 86285; Signal sampled at location ‘AC 2’; red: measured signal, blue: corrected signal

Since, within the used scene, there are just minor land – parts to find, we don´t expect to see the adjacency correction to have any recognizable effect. To still check if there is any correction for the adjacency effect in the spatial context of land parts, we positioned the sample locations as can be seen in . AC 1 is located directly next to some small terrestrial part, while AC 2 is located more offshore. As expected, the adjacency correction, even for AC 1, modifies the radiance – signal just marginally as it is shown in . For AC 2, shown in , there is no recognizable effect at all.

Thus, the adjacency correction works as we expect it to.

- Quality Mask

The chosen scene globally suffers, amongst other parameters like atmospheric conditions and clouds, from strong influence by sun glint. This is shown in , where we adjusted the histogram to make the apparent sun glint more visible. According to that, Figure 7-34 shows the corresponding quality mask. Here, the total quality is mapped in greyscale and, as we expect it, when keeping in mind the apparent sun glint within this scene, most parts are found to be of a quality close to or equal zero, indicating a low quality of this scene.

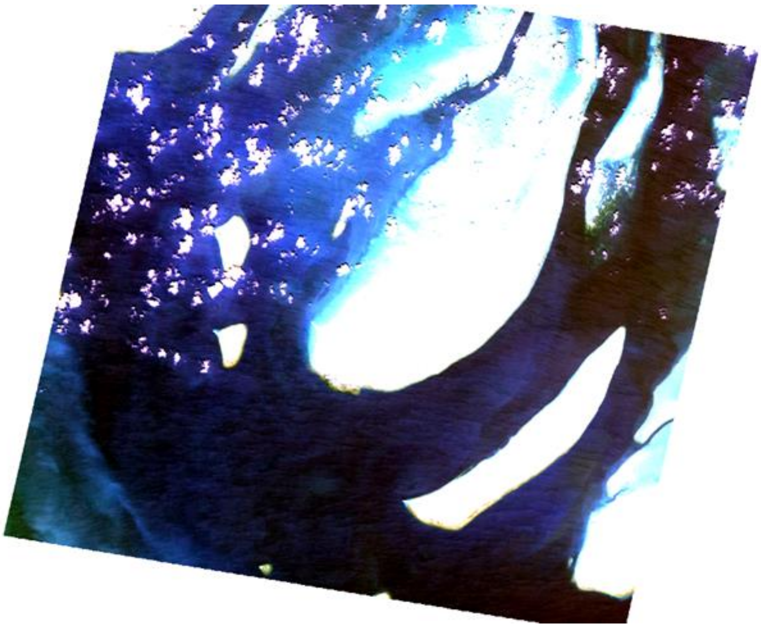


Figure 7-33 Scene-ID 10307; RGB-Quicklook, histogram-stretch with Bands 611.02nm – 550.69nm – 463.73nm

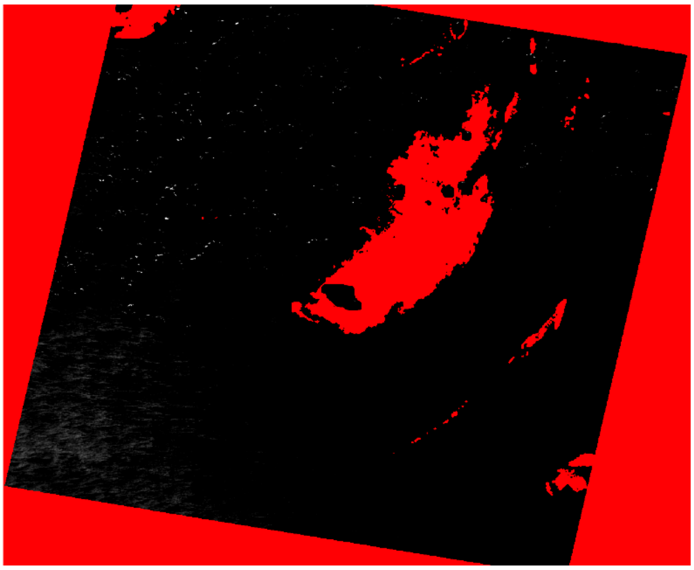


Figure 7-34 Scene-ID 10307; Quality Mask in Grey Scale; Black corresponds to 0, meaning lowest total quality, red is No Data

- Reflectance Product

To get a better impression of the product normalized water leaving reflectance as the final one, Figure 7-35 shows the reflectance using the RGB channels 611.02nm, 550.69nm and 463.73nm.

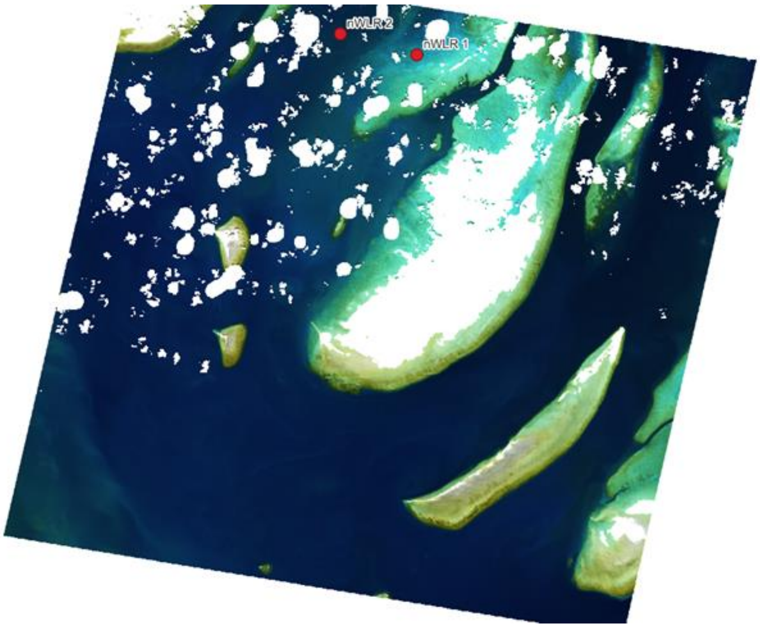


Figure 7-35 Normalized Water Leaving Reflectance of scene-ID 10307; Wavelengths for RGB: 611.02nm – 550.69nm – 463.73nm

For the two labeled locations in Figure 7-35 the sampling coordinates are as follows:

nWLR 1: LAT -13.82622001 | LON 143.92703959

nWLR 2: LAT -13.81729374 | LON 143.89045679

The following two plots, and , depict the normalized water leaving reflectance (nWLR), sampled at the locations nWLR 1 and nWLR 2 (see). nWLR 1 is located at some shallow part of the location, where we can expect the sea floor to influence the reflectance considerably. nWLR2 was placed over deeper water, thus, we expect the seafloor to have much less influence on the signal at all.

These assumptions are confirmed when taking a look at the following figures, and . The first one depicts the spectrum sampled over shallow water and clearly shows the influence of the sea floor, while the latter much more depends on the water column itself.

Summing up, the retrieving of the normalized water leaving reflectance works, as we expect it to.

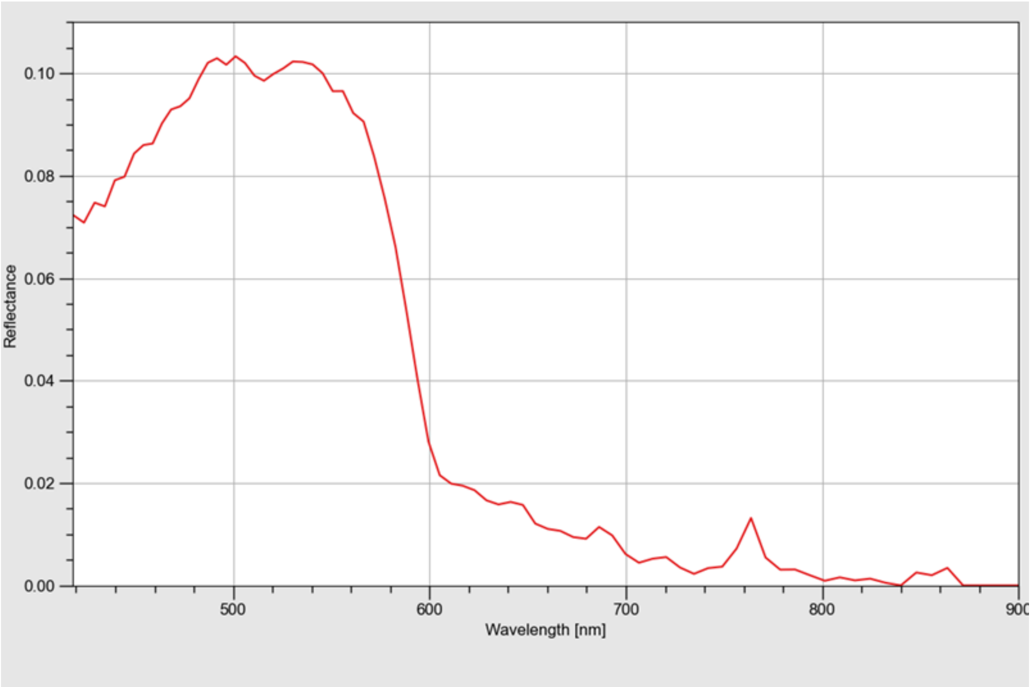


Figure 7-36 Scene-ID 10307; nWLR sampled at location nWLR 1

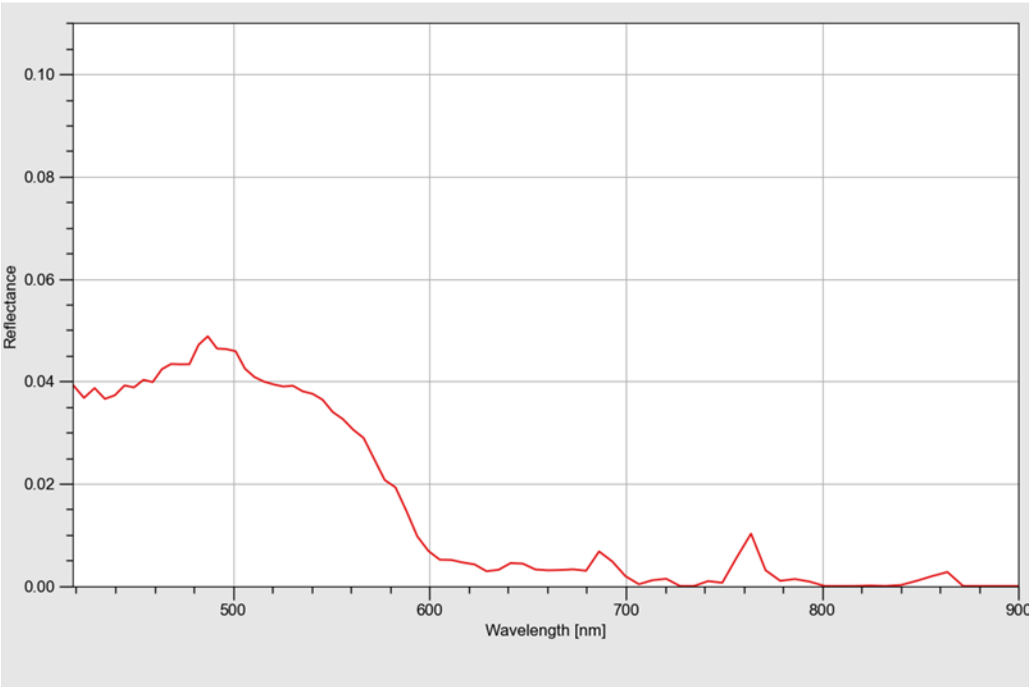


Figure 7-37 Scene-ID 10307; nWLR sampled at location nWLR 2

7.6.4.2 **Validity of generated L2A "land" data**

7.6.4.2.1 Analyzed scenes

Within the time interval between 01.10.2024 to 31.12.2024, an interactive in-depth analysis has been conducted for the following scenes:

Datatake-ID	Tile -ID	date	location	L2A option	cirrus and haze removal	Archived Version	processor version	Overall Quality	Quality Atm
96288	10	2024-10-05	France	Land	No	01.04.02	V010501	Nominal	Nominal
96288	11	2024-10-05	France	Land	No	01.04.02	V010501	Nominal	Nominal
103306	06	2024-11-15	Alps, Germany	Land	Yes	01.05.01	V010501	Nominal	Nominal
103306	07	2024-11-15	Alps, Germany	Land	Yes	01.05.01	V010501	Nominal	Nominal
104138	14	2024-12-04	Sweden	Combined	No	01.05.02	V010501	Nominal	Low
104138	15	2024-12-04	Sweden	Combined	No	01.05.02	V010501	Nominal	Low

Table 7-30 Datatake ID of analyzed land products

For the selection of L2A data, several data takes acquired within the time frame of 1st of October – 31st of December covering different landscapes at different conditions were analyzed.

7.6.4.2.2 Data Checks

In the following, the different tiles were checked for the shape and magnitude of the BOA_ref spectra. Also, the quality of the generated masks is evaluated as well as possible differences in the overlapping areas of neighboring tiles.

For all tiles the visual image impression is fine. For the masking, there are the known issues of mis-classifications of water and cloud shadows and clouds and snow; visual inspection shows that this masking is plausible. The BOA_ref spectra all show the typical shape and magnitude, indicating the correct L2A correction. The overlapping regions between two neighboring tiles match very well (geometrically and spectrally). As expected, the overlapping region between VNIR and SWIR includes the band-to-band changes ("jumps") but outside this region the overall shape and magnitude of the BOA_ref between VNIR and SWIR is accurate.

- Alps

There is still the known problem of misclassifications of steep slope shaded areas classified as water (Figure 7-38) which has also been already described and analysed (ticket #444). In addition, parts of the snow-covered areas are misclassified as clouds, also a well-known masking problem.

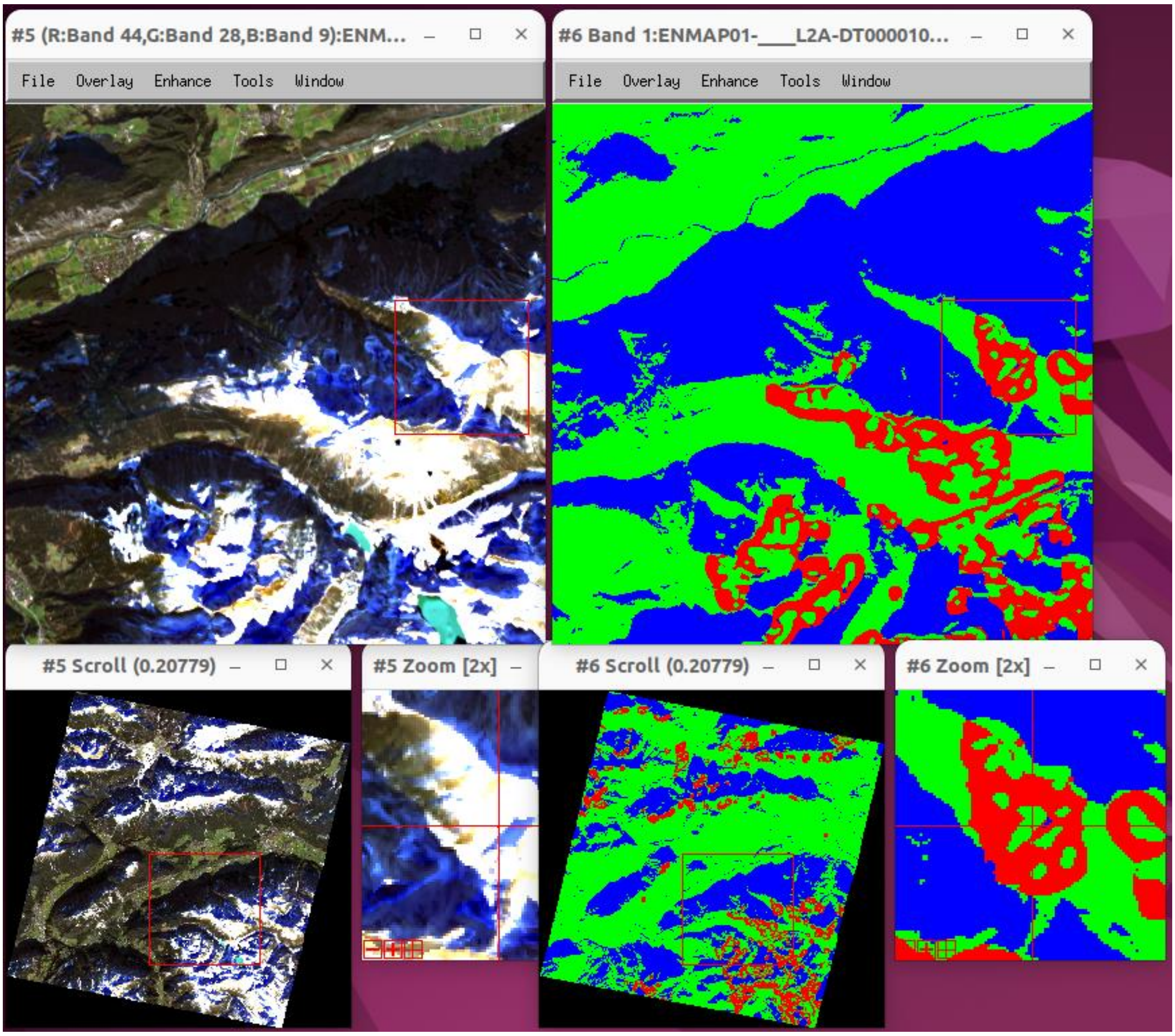


Figure 7-38 EnMAP L2A true colour composite (bands 44-28-9) of scene DT103306 Tile 07 and its corresponding masks (QL quality classes) with blue = water and red = clouds

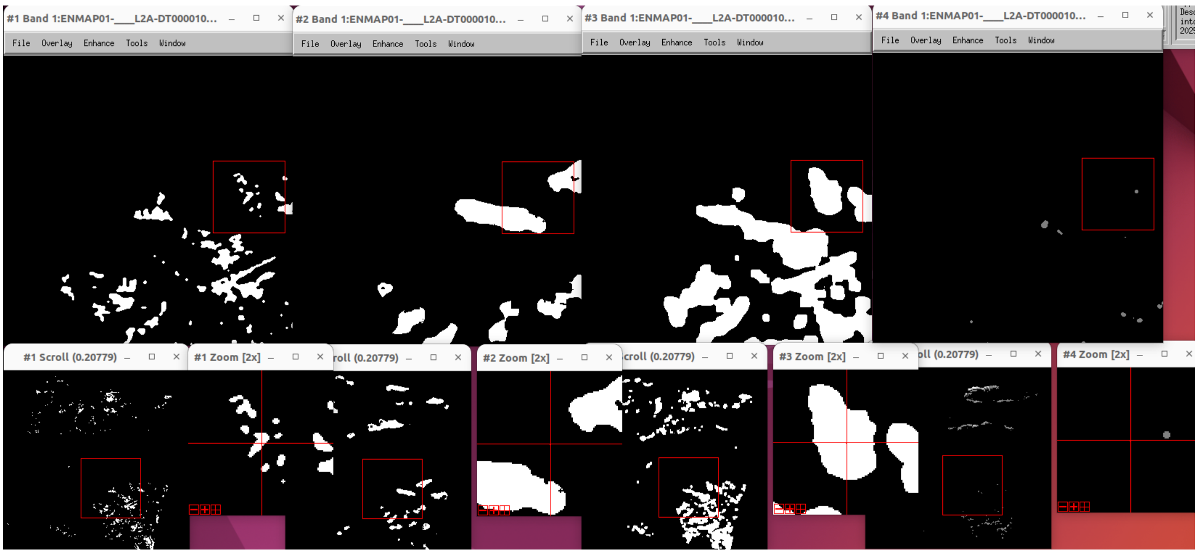


Figure 7-39 Corresponding quality layers (from left to right) snow, cloud shadow, cloud, cirrus

A pixelwise comparison of the BOA reflectance spectra of the overlapping areas of the neighboring tiles 6 and 7 shows a good agreement. The largest differences (still small) can be seen with bright reflectances (snow spectra).

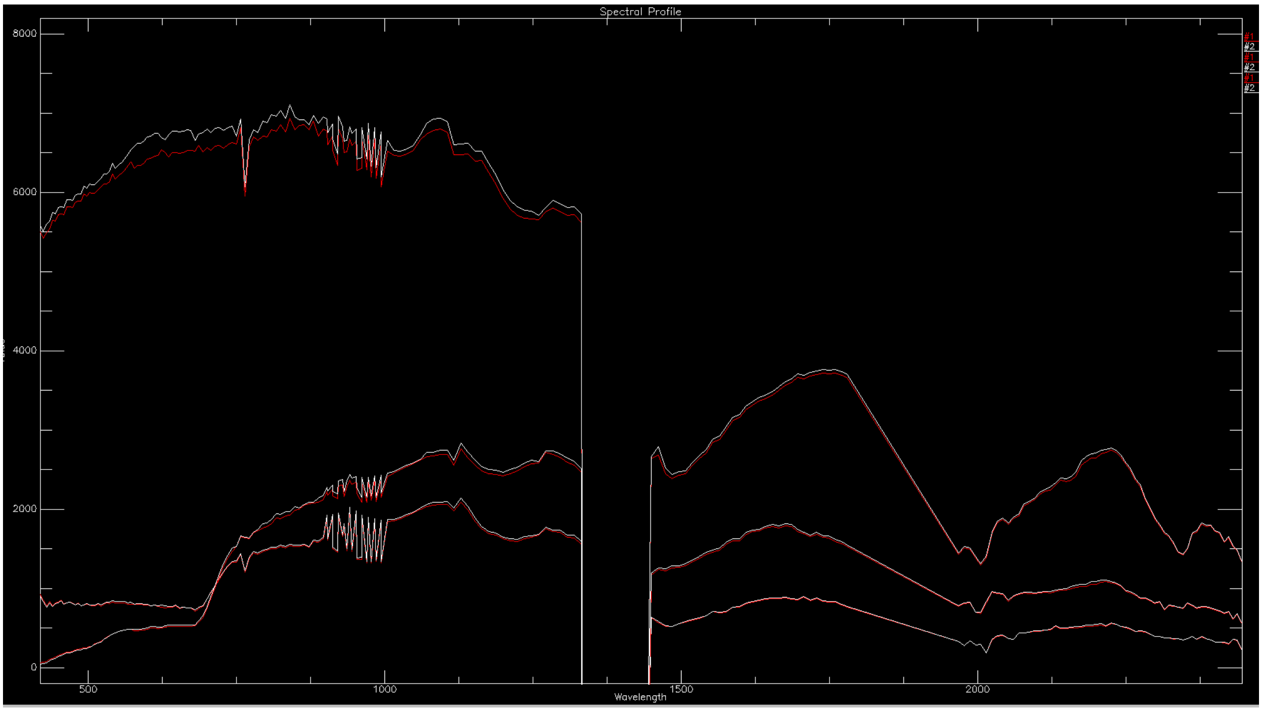


Figure 7-40 Single pixel BOA reflectance spectra of the same pixel of the neighboring tiles

- France

When checking the generated cloud and quality layers, the masking and assignment of clouds is generally valid. Strangely, there is no cloud shadow assigned within the whole image. In some cases, the class labels for water is incorrectly assigned to cloud shadows (Figure 7-41), but this behavior is known and due to the high spectral similarity of these classes, especially when cloud shadows occur over dense dark vegetation (see also ticket #518).

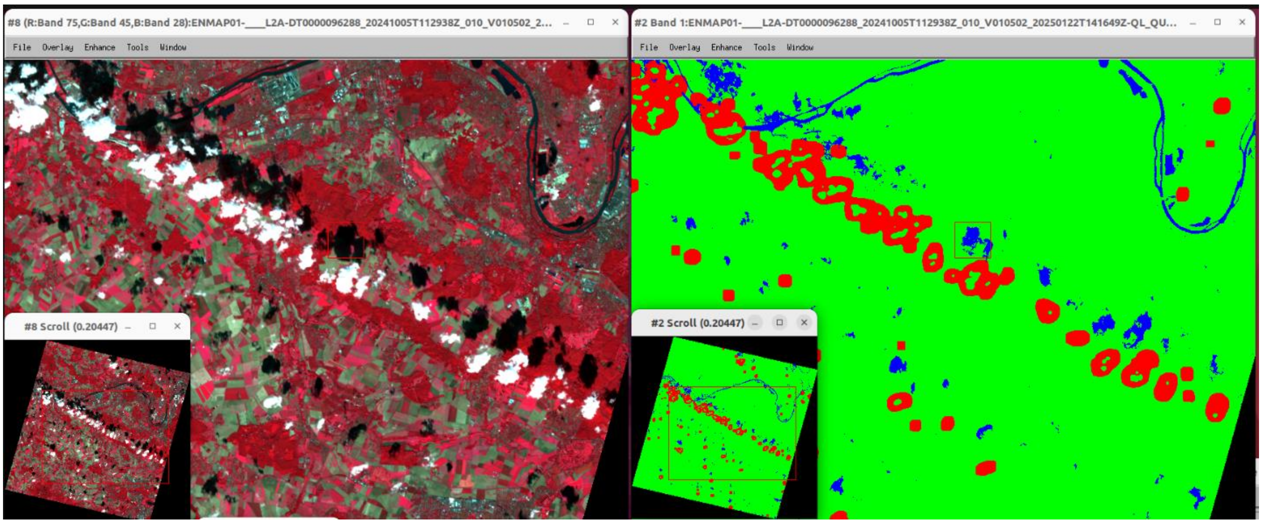


Figure 7-41 EnMAP L2A CIR composite (bands 75-45-28) of scene DT96288 tile 10 and its corresponding masks (QL quality classes) with blue = water and red = clouds

Regarding the non-existent cloud shadows, an ATCOR processing was carried out for comparison (Figure 7-42). The misclassification of water on shaded areas also occur in the ATCOR processed imagery. But in addition, the ATCOR result also classifies cloud shadows. The non-occurrence of cloud shadows in the result of PACO needs to be investigated.

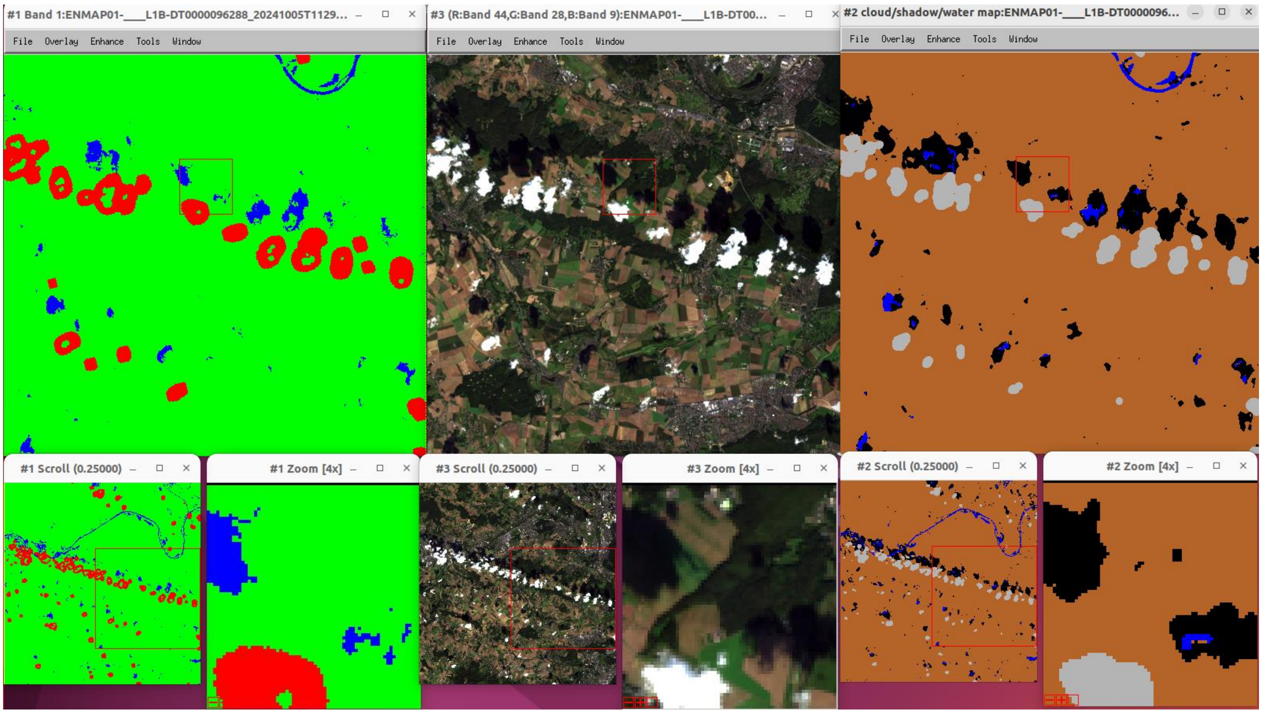


Figure 7-42 Comparison of PACO and ATCOR classification results. Left: PACO masks (QL quality classes) with blue = water and red = clouds; Middle: EnMAP L2A RGB composite (bands 44-28-9) of scene DT96288 tile 10; Right: ATCOR masks (hcw) with blue=water, grey =clouds and black = cloud shadows

The differences between the spectra in the pixel-by-pixel comparison of the overlapping areas of the two neighboring tiles are minimal (Figure 7-43).

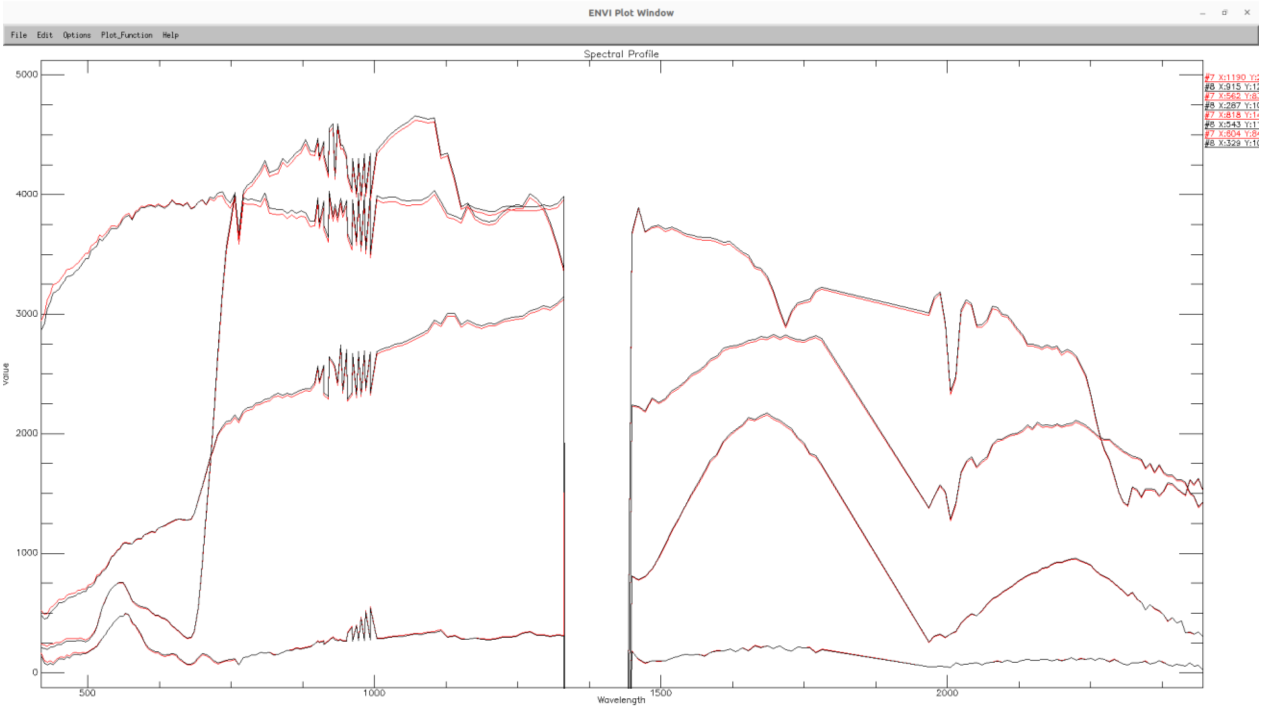


Figure 7-43 Single pixel BOA reflectance spectra of the same pixel of the neighboring tiles

- Sweden, low-light conditions (example for L2A dataset outside the valid SZA range)

This data take has been acquired at a very low sun angle (8° solar elevation), therefore the scene conditions are out of requirements. However, since the data set was obviously requested despite the poor conditions, we examine the L2A results in the following. As this is an area with many lakes, the combined version of the L2A processor was chosen. Probably also due to the solar angle and related unusually low radiance levels, a much larger area is classified as water compared to the actual presence (Figure 7-44). Accordingly, land pixels are incorrectly treated and processed as water. In this particular case, we would rather advise against the combined version.

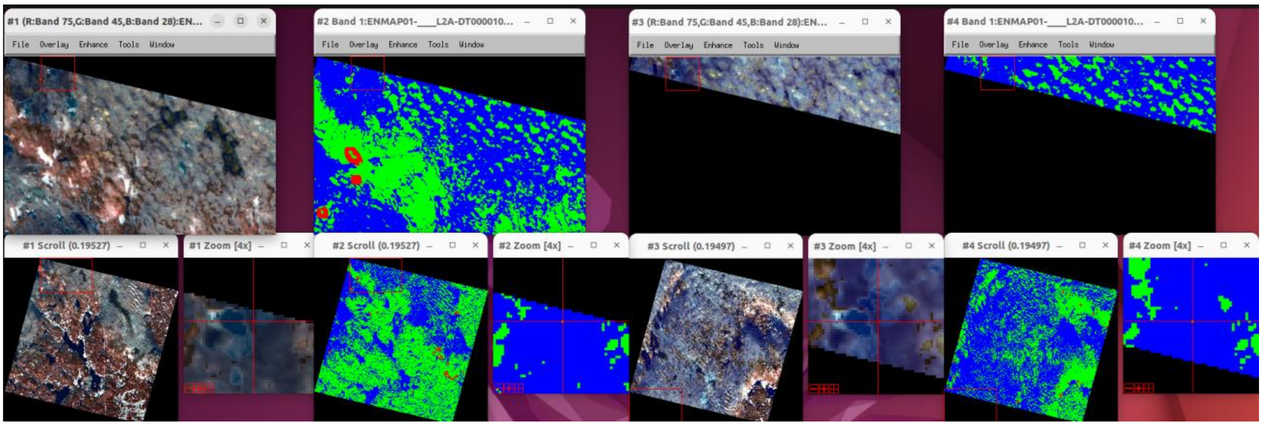


Figure 7-44 EnMAP L2A CIR composites (bands 75-45-28) of scene DT104138 Tiles 14 and 15 and their corresponding masks (QL quality classes) with blue = water and red = clouds of the overlapping area.

The fact that the pixel-by-pixel comparison of the neighbouring tiles shows larger differences, especially in the short wavelength range, is also not surprising. Overall, it can be said that the results are as good as they can be under the given circumstances.

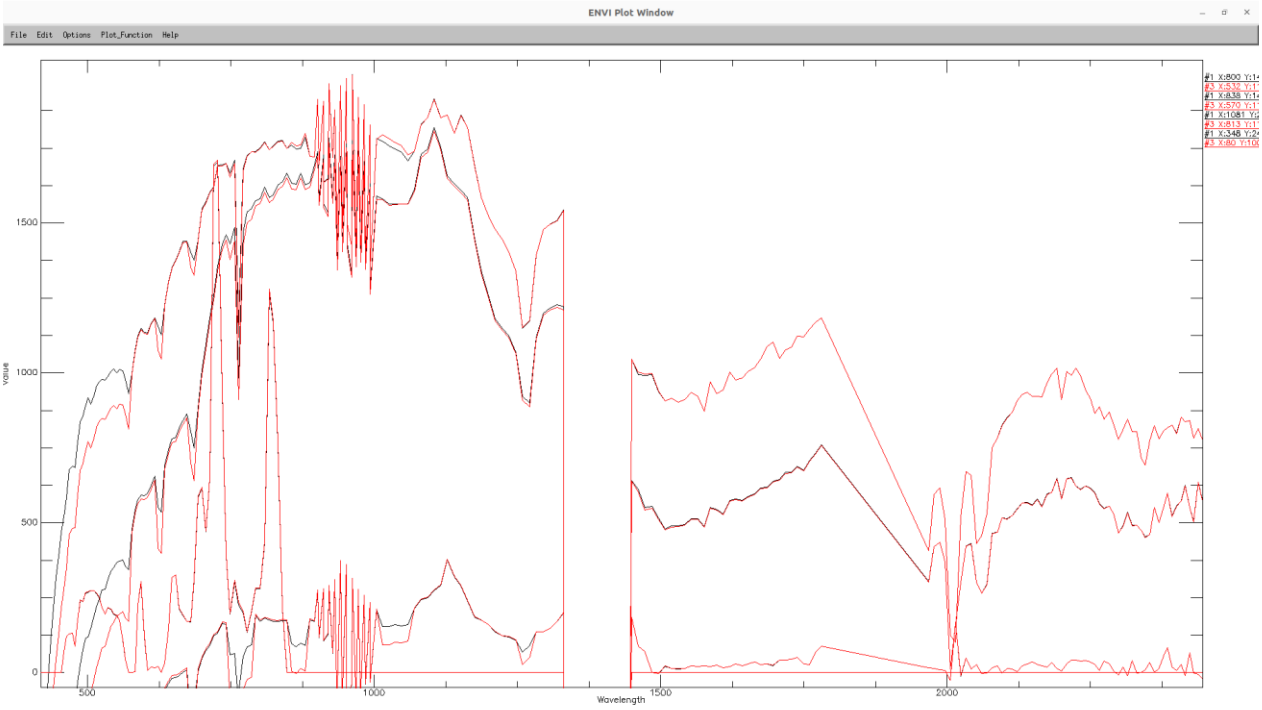


Figure 7-45 Single pixel BOA reflectance spectra of the same pixel of the neighboring tiles

8 External Product Validation

The standard quality parameters were validated in the external product validation process for the reporting period. More than 380 EnMAP products from the latest available processor and archiving versions were downloaded and checked for suitability for validation. Some new matchups with reference measurements could be implemented in the reporting period.

8.1 Level 1B

The following validation scenarios were performed to validate Level 1B products:

- TOA Radiance
- Spatially coherent radiometric miscalibration (striping artifacts; along- and across-track)
- Signal-to-Noise Ratio (SNR)
- Spectral validation

The latest TOA radiance comparisons have confirmed that the radiometric deviation for the significant wavelength ranges is still < 5% RMSE. Minor overshoots in the detector wavelength edge regions and in the water absorption bands cannot be clearly attributed to errors in the EnMAP products, the processing, or the validation data.

No significant anomalies were detected regarding the VNIR and SWIR across-track direction spatially coherent radiometric miscalibration indicating that the implemented correction algorithm works very well. SWIR along-track artifacts at wavelengths with a vital gradient/feature are still visible. However, there are currently no needs to implement a correction, as there are hardly user complaints and a perfect correction is apparently not feasible. The mentioned artifacts are well within the mission requirements of < 5 %.

The SNR assessment was updated based on 196 reprocessed tiles (VNIR 110 and SWIR 86) and was found to be very stable (VNIR: 411:1; SWIR: 263:1) compared to the previous evaluations and inside the mission requirements (VNIR > 343:1 @495 nm SSD 4.7 nm; SWIR > 137:1 @2200 nm & SSD 8.4 nm).

Nine tiles acquired under different atmospheric and angular conditions were used to determine the spectral smile and offset using the O_2 band (761 nm) for the VNIR and CO_2 band (2300 nm) for the SWIR detector. The across-track variations (VNIR: -0.09 nm offset, ~0.33 nm peak to peak and SWIR: 0.38 nm offset, ~0.95 nm peak-to-peak) are always smaller than the requirements (761 nm: 1.72 nm, 2300 nm: 1.55 nm).

8.2 Level 1C

The following Level 1C validation scenarios have been performed:

- VNIR-to-SWIR spatial co-registration
- Absolute spatial accuracy

For the spatial co-registration between VNIR-to-SWIR for products with an archived version ≥ 01.05.02 an RMSE of 5.8 m in X and 6.4 m in Y direction derived from 75 tiles is achieved. Thus, the geometric co-registration has reached a stable level, well inside the mission requirements of < 30 % of a pixel.

The quality of the absolute spatial accuracy is also stable. Once again, an RMSE of 9.9 m in X and 12.2 m in Y derived from 51 tiles with an archived version ≥ 01.05.02 was achieved which is well inside the mission requirements (<30 m with GCPs in the image, <100 m without GCPs).

8.3 Level 2A

Eleven new in-situ matchups were added to the L2A land and water quality assessment during the last quarter.

Land

Three new matchups increased the total number of successful matchups to 50. The results stabilized the uncertainty pattern and thus confirmed the fulfilment of mission requirements for BOA reflectance. New validation efforts with field teams failed due to lack of EnMAP applications in this quarter. Similar to the TOA radiance product, at the beginning (<500 nm) and ending (>2400 nm) of the wavelength domain, slightly higher residuals (up to 3% RMSE, accuracy, and precision) can be identified. The majority is around 2% for the rest of the wavelength domain. All measures are generally well inside the mission requirements for BOA reflectance of 5%.

The previous observations that the uncertainty of the SWIR is generally somewhat too high were examined for the first time on the basis of an individual analysis of two RadCalNet test sites. This also made the influence of the reference measurements clear. Although the uncertainty results for Gobabeb (GOBA) and Railroad Valley Playa (RVP) are similar in the VNIR (with slightly lower values for RVP), the situation in the SWIR is exactly the opposite, with values for RVP that are twice as high and clearly above the requirement. Since calibration differences can actually be ruled out for the stations, the difference must be due to other factors such as the BRDF, which has not yet been taken into account.

For the VNIR range, it must also be said that there are often insufficient dark vegetation pixels in the test sites, so that the EnMAP L2A processing falls back on the default AOT value, which results in higher uncertainty values.

Water

Eight new valid matchups of normalized water leaving reflectance could be integrated into the statistics of this report. Compared with the previous processor version v01.04.02, the validation based on v01.05.02 showed lower reflectances for Lake Garda (deep subalpine glacial lake) and Lucinda (coastal water), however, for other sites such as Rio de la Plata (highly turbid water) or Lake Trasimeno (shallow tectonic lake) there are only marginal differences. Spectral noise in dark water persists in processor version v01.05.02 but the differences to previous processors might be in the area of signal-to-noise. Overall, the water validation results show a clear fulfilment of the mission requirements.

8.4 Summary of External Product Monitoring

No anomalies or non-compliance with the mission requirements were identified. All validation and quality monitoring efforts during the reporting period indicated that the EnMAP product quality is stable and respective mission requirements are fulfilled.

9 Others

EnMAP Mission Operations and Status Publications:

- Chabrillat, S., Foerster, S., Segl, K., Beamish, A., Brell, M., Asadzadeh, S., Milewski, R., Ward, K., Brosinsky, A., Koch, K., Scheffler D., Guillaso S., Kokhanovsky, A., Roessner, S., Guanter, L., Kaufmann, H., Pinnel, N., Carmona, E., Storch, T., Hank, T., Berger, K., Wocher, M., Hostert, P., van der Linden, S., Okujeni, A., Janz, A., Jakimow, B., Bracher, A., Soppa, M. A., Alvarado, M. A. L., Buddenbaum, H., Heim, B., Heiden, U., Moreno, J., Ong, C., Bohn N., Green, R., Bachmann, M., Kokaly, R., Schodlok, M., Painter, T. H., Gascon, F., Buongiorno, F., Mottus, B., Brando, V.E., Feilhauer, H., Betz, M., Baur, S., Feckl, R., Schickling, A., Krieger, V., Bock, M., La Porta, L., Fischer, S. (2024), The EnMAP spaceborne imaging spectroscopy mission: Initial scientific results two years after launch, Remote Sens. Environment, 315, 114379. https://doi.org/10.1016/j.rse.2024.114379

EnMAP Mission Operations and Status Presentations:

- Presented at Oceans Optics (6–11 Oct 2024): “The EnMAP Ground Segment Processor for aquatic applications” (N Pinnel et al.)
- Presented at 2nd Workshop of the CARF Remote Sensing (16–17 October 2024):
  - “Application and collaboration opportunities within EnMAP“ (S. Baumann et al.)
  - "Initial science results two years after launch" (S. Chabrillat et al., representative R. Milewski)
- Presented at 3rd Workshop on International Cooperation in Spaceborne Imaging Spectroscopy | Hyperspectral 2024 (13–15 Nov 2024):
  - “EnMAP Mission status overview and observing strategy” (Laura La Porta et al.)
  - “Lessons learned from EnMAP in-orbit calibration and product harmonization for upcoming space-based hyperspectral missions” (Miguel Pato et al.)
  - “EnMAP product validation and on-orbit mission cross-validation” (M. Brell et al)
  - “EnMAP hyperspectral mission: Developments and demonstration for spaceborne imaging spectroscopy open science” (S. Chabrillat et al.)
- Presented at WHISPERS 2024 (9–11 Dec 2024):
  - “EnMAP operations in the light of data product statistics” (M. Habermeyer et al)
  - “The German hyperspectral Mission EnMAP – Mission status overview and observing strategy (V. Krieger et al.)