Deutsches Zentrum
für Luft- und Raumfahrt e.V.
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EnMAP Ground Segment

Mission Quarterly Report #08

01.04.2024 to 30.06.2024

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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 eighth Mission Quarterly Report (MQR) applies to the operations of EnMAP in the reporting period of Routine Phase (RP) from **01.04.2024** to **30.06.2024 (Q2/2024)**.

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 between 01.04.2024 and 30.06.2024 there have been no major issues affecting the instrument or the satellite. The mission has been operating normally with only one outage of 2 days duration (08-09 June 2024) caused by a software problem in the planning system after the introduction of the new Back-to-Back imaging mode during Q2 2024. There have been no further issues with the thermal control system of the instrument after a software update was performed January 24. Like in previous quarter, the mission is regularly reaching and surpassing, the initial maximum acquisition capacity of 5000 km / day thanks to the changes introduced during the last year.

In this period, 1713 Earth observations of 30 km swath width and up to 990 km swath length were successfully performed which resulted in 18226 archived Earth observation tiles of 30 km × 30 km and 25 calibration acquisitions. In addition, 14722 products were delivered from catalog orders. In total, 10772 Earth observations were performed until 30.06.2024 by the EnMAP team and the 2006 registered Science users. This results in 82159 archived Earth observation tiles (117859 products including re-processed products with different versions) and 146226 Earth products delivered to users from observations requests (80527) and catalogue orders (65699) since the start of the mission. More details are presented in Section 5 and 6.

The following limitations are applicable at 30.06.2024:

- Some striping effects in SWIR data in the along-track direction more visible in uniform areas with a strong spectral gradient.
- Between 16 and 22 April and during May 3., the maximum limit of requests was reached again in the planning system, causing a delay for new requests to enter the system. Acquisition requests were buffered during this period and resubmitted at a later time, but some of them could have exceeded their validity time window at the time of being considered, what leads to their cancellation.

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:

- Implementation of back-to-back imaging that reduces the minimum distance between consecutive acquisitions (from ~2750 km down to ~730 km) for up to 3 consecutive acquisitions.
- Several updates on the Instrument planning portal, including:
  - Blocking of L0 orders for non-internal users
  - Restriction of the acquisition time window to 3 months and
  - Reduction of the priority from 4 to 0 for Cat-1 users when their quota is exhausted (blocking of ordering options)
  - Restriction of selectable roles for external users
  - Visual appearance of the Planning Portal and adaptation of the landing page
- Re-processing of archived products is in progress. Priority processing is now assigned to the oldest data (commissioning phase). On these data the co-registration errors are larger, what makes the re-processing of the data more necessary for them. 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. The re-processing will continue over the coming months. For more details on geometric performance check Section 7.6.3.
- Announcement of new priority observations, Foreground Mission, in the EnMAP web site (https://www.enmap.org/data_tools/foreground_mission/).
- Change log with information for users about the Ground Segment data processing software has been made available at https://www.enmap.org/data/doc/EnMAP_processor_changelog.pdf.

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

- Correction of radiometric striping in the along-track direction.
- Complete re-processing of archived data (see note above concerning re-processed data improvements).
- Implementation of measures to improve planning and acquisition activities.
- Implementation of new linearity calibration (and updated calibration) to improve the VNIR-SWIR matching between spectrometers, specially at low radiances

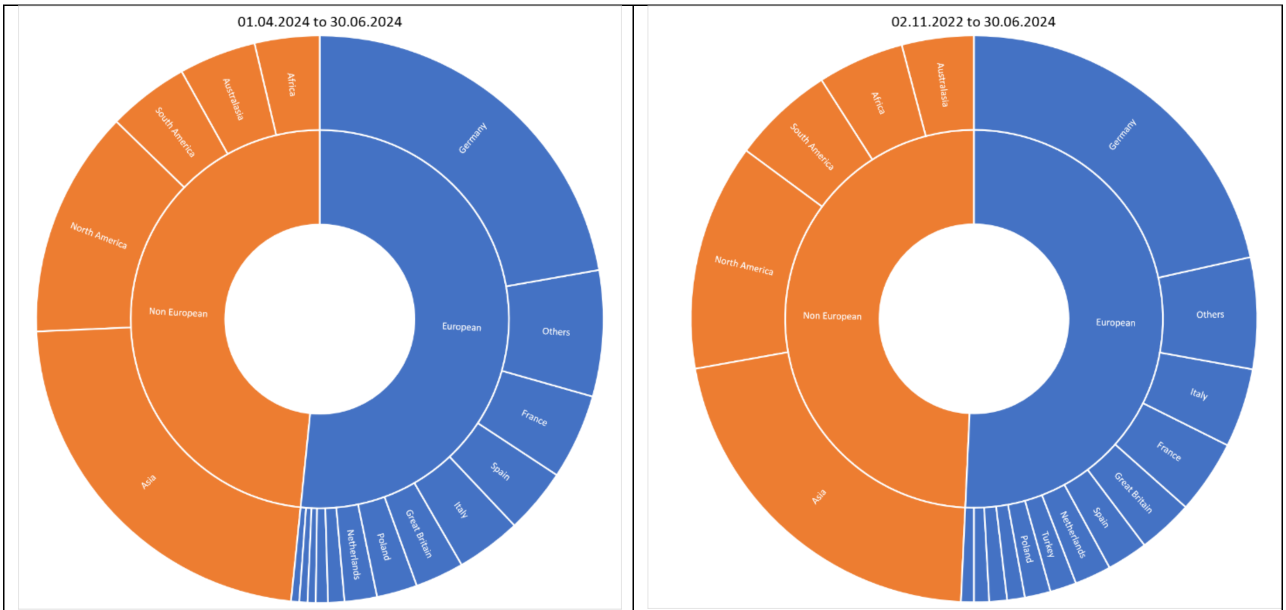
5 Users and Announcements-of-Opportunities

5.1 Users

	Country/*Continent (No of Countries)*	Reporting Period 01.04.2024 to 30.06.2024	Since beginning of routine Phase until 30.06.2024 (end of reporting period)
Total European Users	*Europe (24)*	223	1654
European	• Germany	96	701
	• Italy	16	147
	• France	21	137
	• Great Britain	12	103
	• Spain	16	76
	• Netherlands	8	68
	• Portugal	3	28
	• Turkey	2	49
	• Greece	2	33
	• Belgium	4	33
	• Poland	10	48
	• Austria	2	24
	• Others (12)	31	207
Non European	*North America (2)*	56	422
	South America (6)	20	190
	Asia (18)	98	699
	Africa (10)	16	161
	Australia + New Zealand (2)	19	134
	Total (62)	432	3260
	*Rejected**	40	49

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

*Users are rejected because of, e.g. EU sanction list checks, data policy or license violations.



Reporting Period 01.04.2024 to 30.06.2024 with a total of 432 Users of 60 different countries.

Since beginning of operational phase until 30.06.2024 (end of reporting period) with total of 3260 Users of 90 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 01.04.2024 to 30.06.2024	Since beginning of routine phase start until 30.06.2024 (end of reporting period)
Registered users	Total	432	3260
	with role assignment*	390	2516
Cat-1 Science	Total	312	2006
	AO Process 00001	312	1901
	AO Process 00002	0	621
	AO Process 00003	0	196
Cat-1 Distributor**	Total	347	1975

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

*Registered users with at least one user role assignment

**Catalogue User, ordering EnMAP data from archive

5.2 Announcements-of-Opportunities

Announcement-of-Opportunity	New within reporting period 01.04.2024 to 30.06.2024			Since beginning of routine Phase until 30.06.2024 (end of reporting period)		
	Proposals	Total tiles requested	Total tiles granted	Proposals	Total tiles requested	Total tiles granted
A00001	72	4398	1193	438	28994	14729
A00002	0	0	0	123	20430	9339
A00003	0	0	0	4	151	97
Total	72	4398	1193	565	49575	24165

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 01.04.2024 to 30.06.2024			Since beginning of routine Phase until 30.06.2024 (end of reporting period)		
		Proposal	Total tiles requested	Total tiles granted	Proposal	Total tiles requested	Total tiles granted
	VEGETATION	26	1689	453	223	26315	11260
	GEO/SOIL	24	1250	424	169	7138	4232
	WATER	8	1194	85	71	5057	2847
	SNOW/ICE	1	3	3	14	1990	806
	URBAN	1	60	8	9	834	315
	ATMOSPHERE	4	108	78	22	3194	1294
	HAZARD/RISK	1	32	32	11	340	283
	METHODS	2	8	5	15	945	542
	CAL/VAL	5	54	105	31	3762	2586
	Total	**72**	**4398**	**1193**	**565**	**49575**	**24165**

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 01.04.2024 to 30.06.2024		Since beginning of Commissioning Phase until 30.06.2024 (end of reporting period)	
			Number Tiles / Observations	Size (in GB)	Number Tiles / Observations	Size (in GB)
Earth Observation (EO)	Yes	Total	18226 / 1713	8731.84	82159 (117859*) / 10772	55002.80
		Average / Day	200.28 / 18.82	95.95	149.71 / 13.10	66.90
	No	Total	37		910	
		Average / Day	0.40		1.10	
Calibration (CAL)	Yes	Total	25	104.39	334	1332.05
		Average / Day	0.27	1.14	0.38	1.62
	No	Total	1		3	
		Average / Day	0.010		0.003	

Table 6-1 Number and size of archived and not archived products (*Number of products including different processing versions)

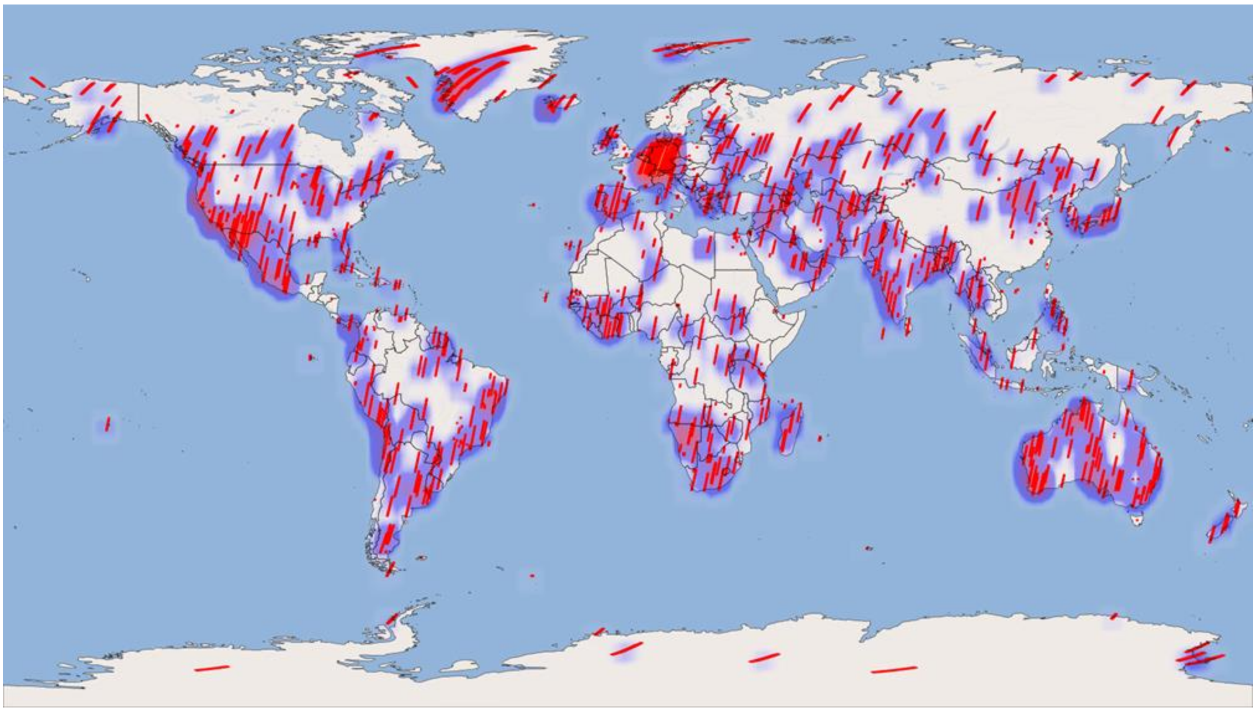
The following table shows the number of delivered products and their sizes within the specified time frames. Product deliveries result either directly from acquisition orders ("Observation") or catalog orders ("Archive").

Type	Delivered		Reporting Period 01.04.2024 to 30.06.2024		Since beginning of Commissioning Phase until 30.06.2024 (end of reporting period)	
			Number Tiles / Observations	Size (in GB)	Number Tiles / Observations	Size (in GB)
Earth Observation (EO)	Observation	Total	19263 / 1350	8516.38	80527 / 8162	35240.31
		Average / Day	211.68 / 14.83	93.58	97.96 / 9.92	42.87
	Archive	Total	14722	83983.454	65699	366503.56
		Average / Day	161.78	922.89	79.92	445.86
Calibration (CAL)	Observation	Total	22	100.51	171	757.52
		Average / Day	0.24	1.10	0.20	0.92
	Archive	Total	0	0.0	67	3486.14
		Average / Day	0.0	0.0	0.08	4.24

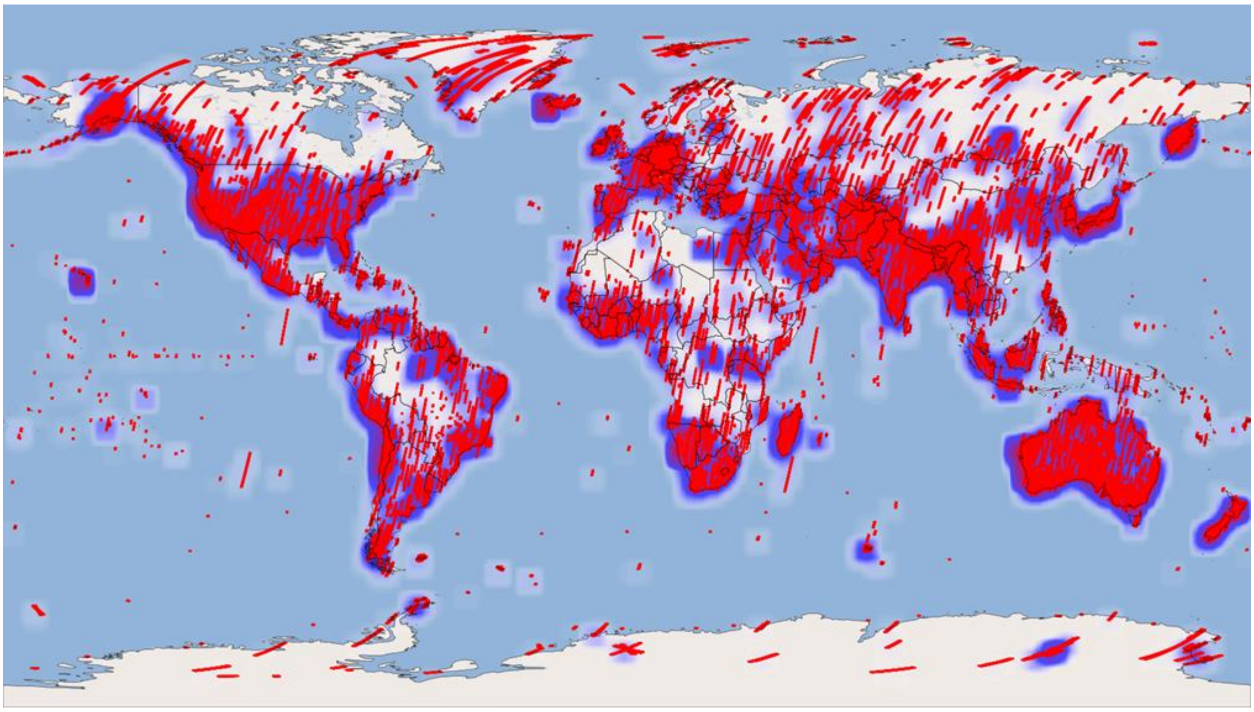
Table 6-2 Number and size of delivered products

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.

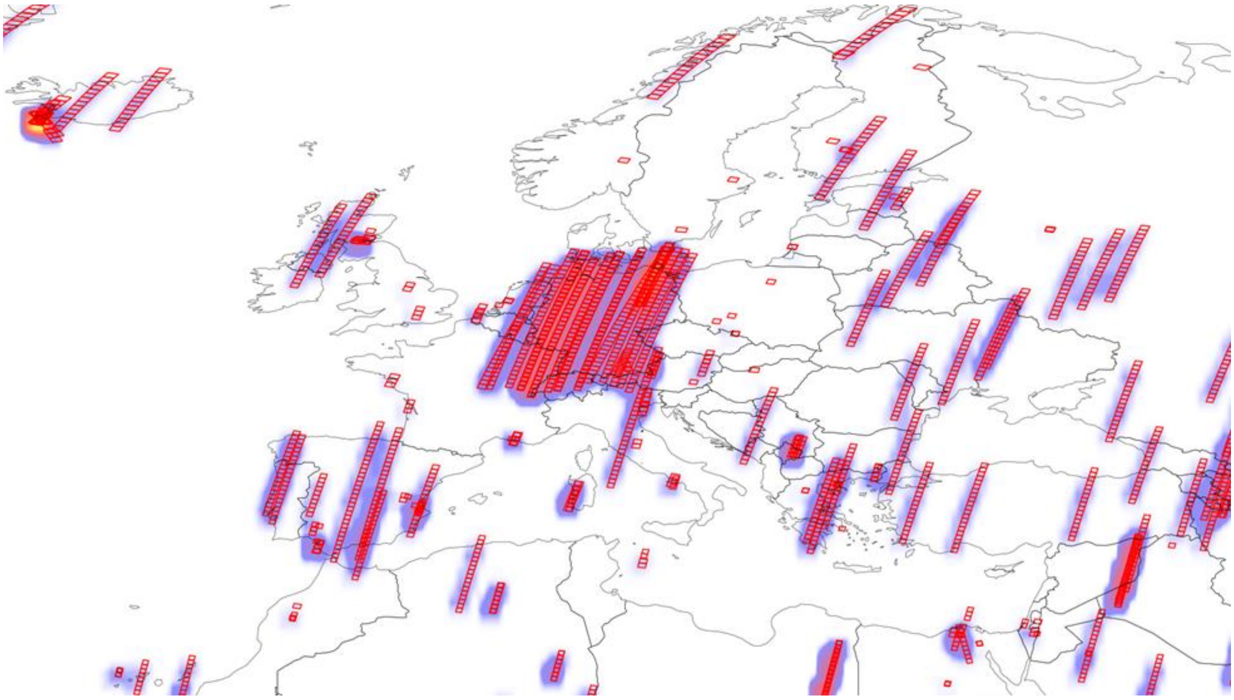


reporting period 2024-04-01 to 2024-07-01 with 17920 tiles

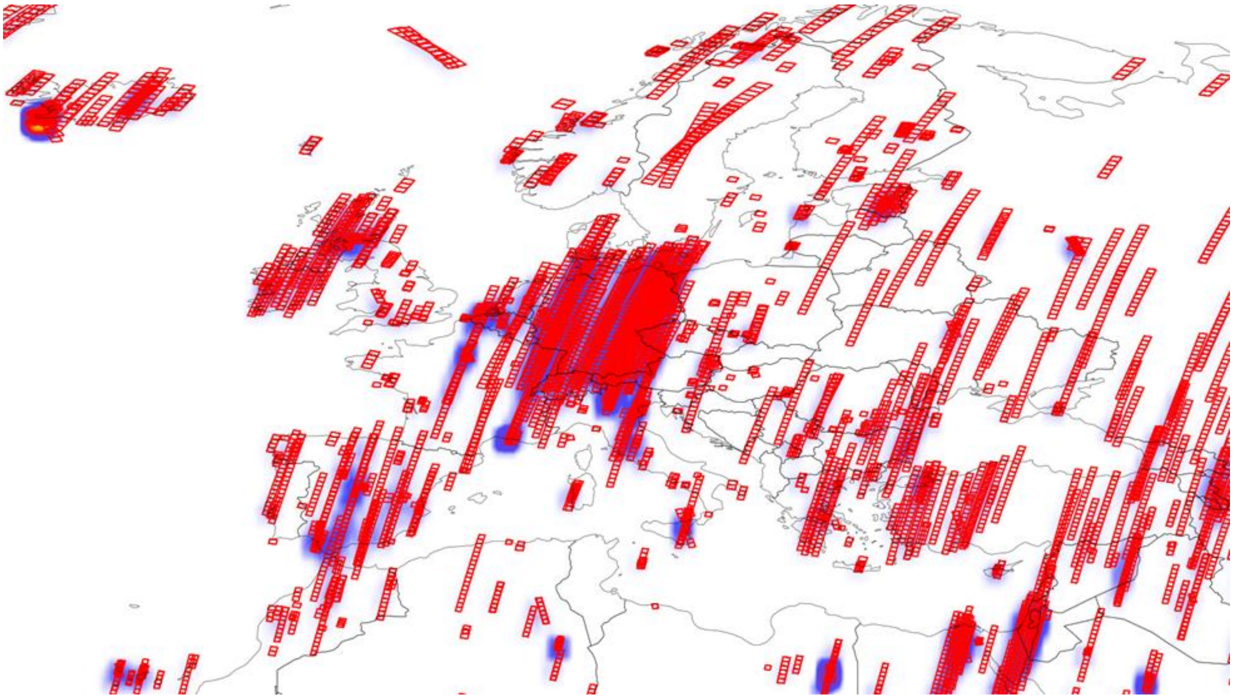


reporting period 2022-04-01 to 2024-07-01 with 112880 tiles (includes commissioning phase acquisitions)

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



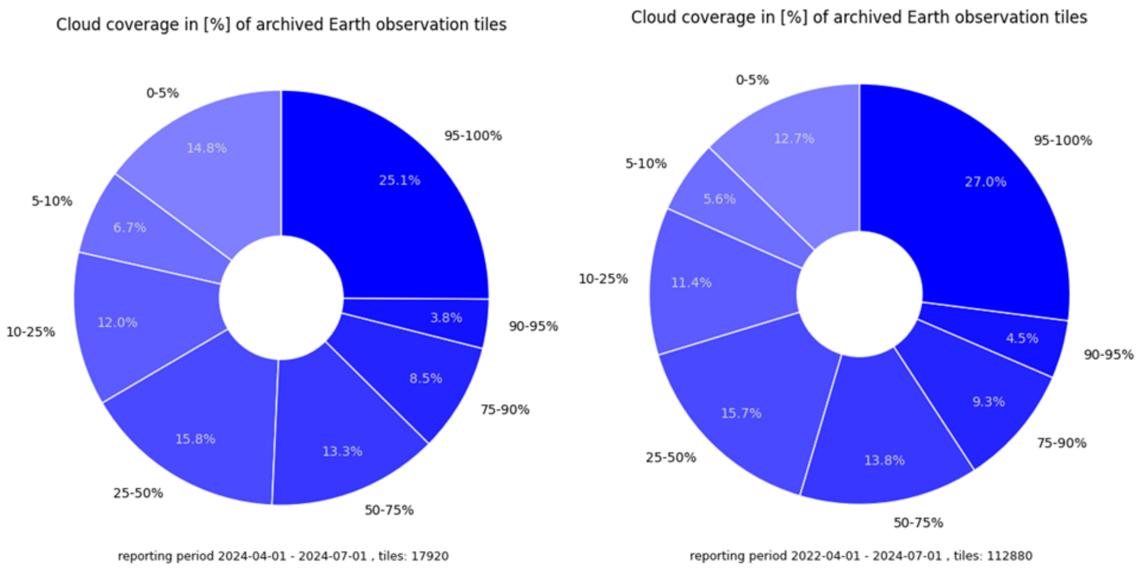
reporting period 2024-04-01 to 2024-07-01 Europe



reporting period 2022-04-01 to 2024-04-01 Europe (includes commissioning phase acquisitions)

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

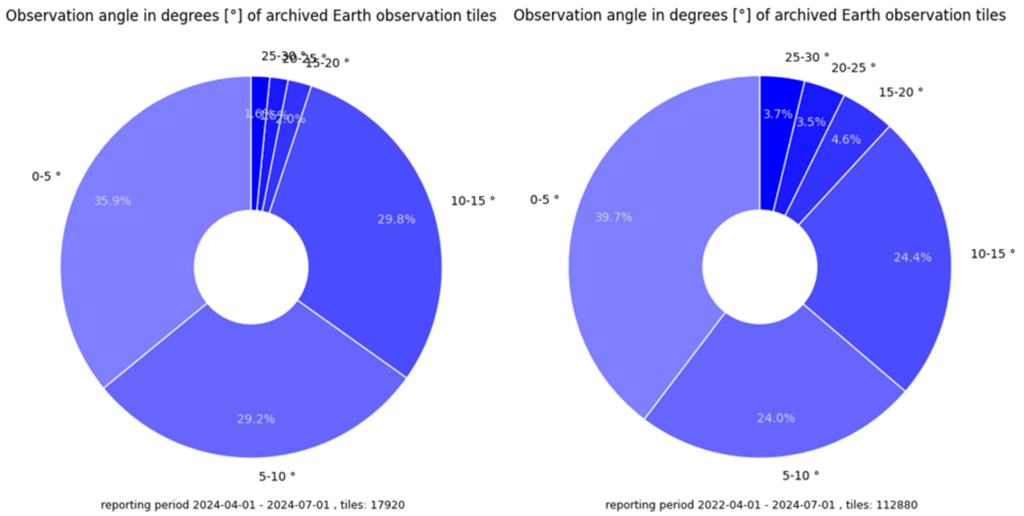
The following figures show the distribution of cloud coverage for the archived products.



2024-04-01 - 2024-07-01, tiles 17920 until 2024-07-01, tiles 112880 (includes commissioning)

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

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

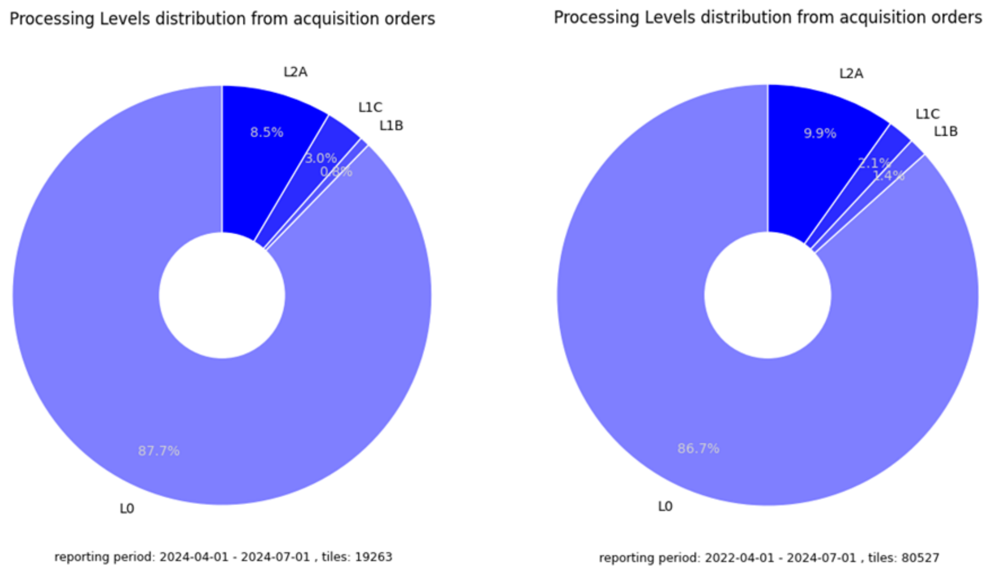


2024-04-01 - 2024-07-01, tiles 17920 until 2024-07-01, tiles 112880 (includes commissioning)

Figure 6-4 Observation angle of archived Earth observation tiles

6.2 Delivered Observations

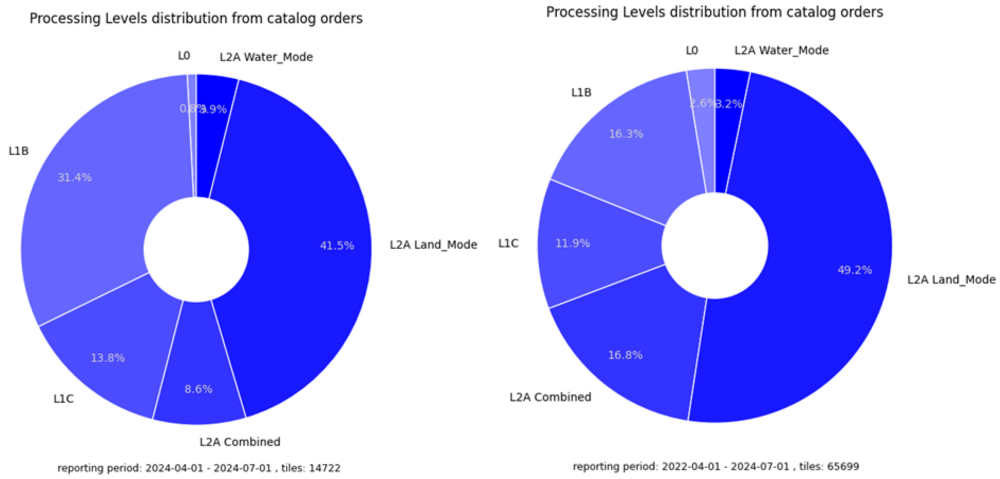
The following figures show the distribution of processing level of the delivered products from acquisition orders.



reporting period 2024-04-01 - 2024-07-01 , tiles 19263 until 2024-07-01 , tiles 80527 (includes commissioning)

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.



reporting period 2024-04-01 - 2024-07-01 , tiles 14722 until 2024-07-01 , tiles 65699 (includes commissioning)

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

7 Detailed Status

7.1 User Interfaces

Further improvements to the user interfaces are continuously on-going and will be reported in this section.

The Instrument Planning tool received updates during the reporting period:

- On 07.05.2024 the deployment on the productive environment, with the content:

  - Blocking of L0 orders

  - Correction of the L2A error for the L2A product correction type

  - Display of the Status column in the MyDatatakes overview

  - Restriction of the acquisition time window to 3 months and

  - Reduction of the priority from 4 to 0 for Cat-1 users when their quota is exhausted (blocking of ordering options)

  - Visual appearance of the Planning Portal

- On 19.06.2024 Deployment on the productive environment, with the content:

  - Restriction of selectable roles for external users: The selectable roles for external users are: cat1, cat-1distributor

  - Adaptation of the landing page of the planning portal

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/

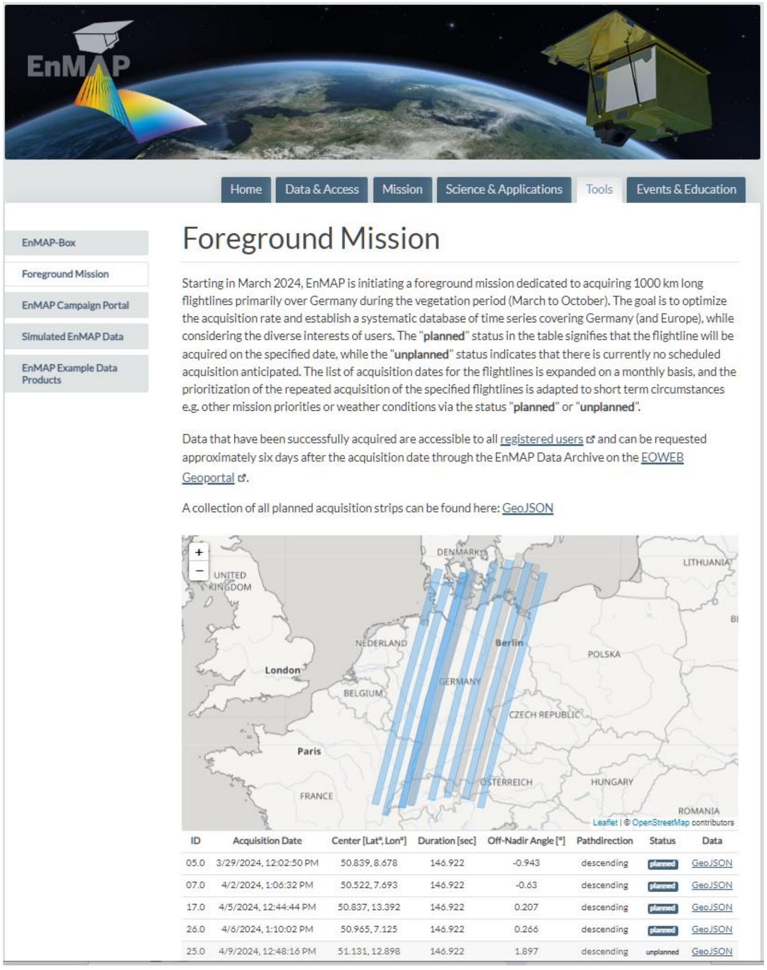


Figure 7-1 Image of the Foreground mission tool available at the EnMAP web site. The map is interactive and the user can download a GeoJSON file with the planned acquisitions.

With this tool the users can get informed weeks in advance about future priority observations with EnMAP. Initially, a set of 10 flight-lines over Germany have been identified together with the user community and will be regularly scheduled until Autumn 2024. New regular flight lines on other locations are also announced in the Foreground Mission page.

7.2 Satellite

No major satellite issues have been observed in the reporting period.

On the ground systems, the number of acquisition requests in the planning system continues to be relatively high what triggers the buffering of the excess of requests in the system. This mechanism prevents the saturation of the system, but can cause tasking requests being buffered until they are considered. During the reporting period this situation happened between 16 and 22 April and on 03 May 2024.

During the reporting period the Mission Planning System of the EnMAP Ground Segment has introduced the Back-to-Back operation mode. This mode allows to perform up to 3 consecutive Earth observations while the satellite keeps the precise pointing mode, allowing for a significant reduction of the distance between consecutive Earth observations (from ~2750 km down to ~730 km). The Back-to-Back imaging mode is active since 25.04.2024. The introduction of this mode created some minor issues and challenges during Q2 2024, the most severe being a two-day outage over the weekend on 08 and 09 June. By the end of Q2 and beginning of Q3 2024 these issues have been solved and the Back-to-Back planning works as intended.

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 (lateral deviation of at most 22 km at equator and altitude deviation of at most 6 km).

During the reporting period, a total of 1118 ACS Precise Modes were executed on-Board, compared to 1988 during the previous quarter. One reason for the lower number of ACS Precise Modes is the accumulation of Image Acquisitions within one Back-to-Back sequence. 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 2024 Q2, a total of three in-plane maneuvers were executed. No out-of-plane orbit maneuvers or collision avoidance maneuvers were required.

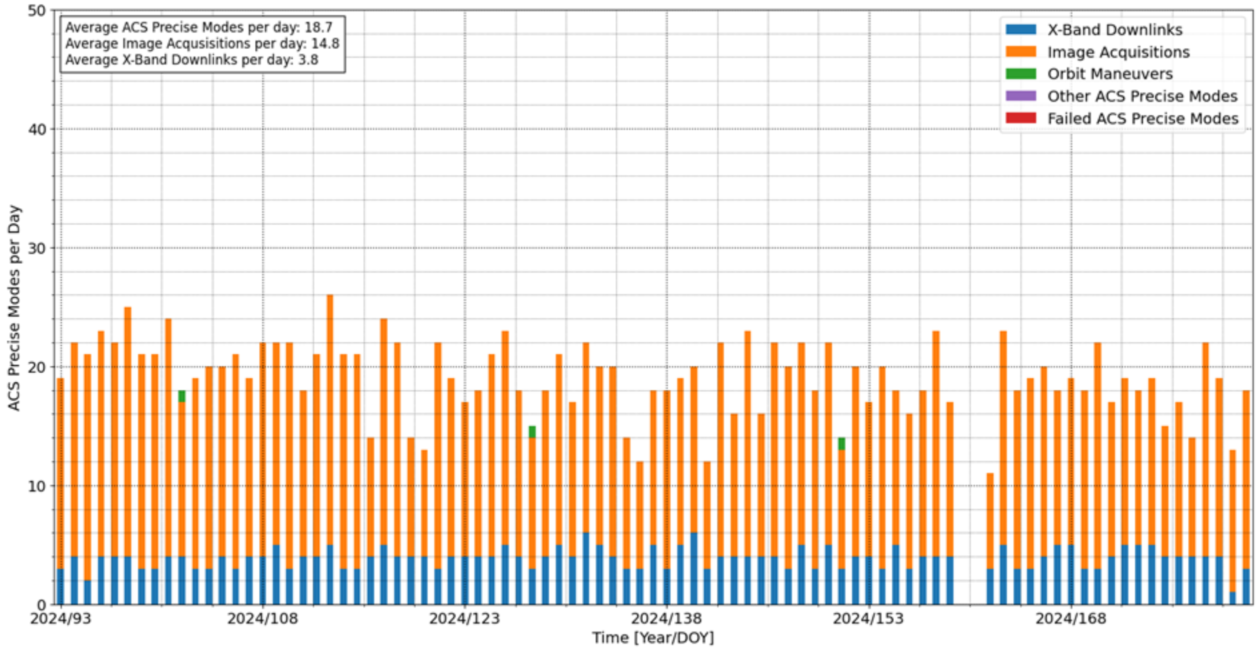


Figure 7-2 Number of ACS Precise Modes per day during 2024 Q2

7.2.2 Life Limited Items

Life-Limited Item	01.04.2024 to 30.06.2024	until 30.06.2024	Estimated total usage
Fuel	+0.2 kg	6.2 kg	>15 years
Battery and Solar Cells	nominal	nominal	nominal
Shutter Usage	+2,00%	12,61%	17,8 years (@ daily use)
FAD movements	+1,00%	22%	15,2 years (@ bimonthly use)
Diffuser exposure time based on sole measurement time	+1,67%	36,67%	8,6 years (@ bimonthly use)
Diffuser exposure time based on real cyclogram duration	+1,98%	43,62%	7,0 years (@ bimonthly use)

On-Board Calibration Equipment Usage	On-board calibration equipment:		
- OBCA SPC lamp 1	+1,20%	10,64%	19,3 years (@ biweekly use)
- OBCA RAD lamp 1/LED 1	+3,13%	19,83%	8,1 years (@ weekly use)
- FPA LEDs 1	+0,56%	5,43%	44,3 years (@ monthly use)

Table 7-1 Status of life-limited items

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	01.04.2024 to 30.06.2024		
	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)	538 (381 WHM, 148 INU)	9	8

Table 7-2 S-Band Ground Station Passes

7.3.2 X-Band

X-Band Ground Stations	01.04.2024 to 30.06.2024	
	Executed Passes	Successful Passes
All stations (Neustrelitz-Germany, Inuvik-Canada)	348 (266 NZ, 82 INU)	343 (263 NZ, 80 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).

In Q2 2024, a change log documenting the history of EnMAP processor updates was introduced and can now be downloaded from the EnMAP website:

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

In the reporting period (01.04.2024-30.06.2024) there was no processor update and **V01.04.02** continues to be the most up-to-date version of the EnMAP processors.

The following limitations are applicable as of 30.06.2023:

- 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 correction is implemented and being tested since V01.04.01, but not active by default.

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	01.04.2024 to 30.06.2024	
	Number of Archived Observations	Size (in GB)
Total	25	108.4
Deep Space	3	3.9
Rel. Radiometric	12	46.8
Abs. Radiometric	1	1.3
Linearity	3	51
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 7-3 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. The effect on the radiometric calibration coefficients of a few selected bands is shown in Figure 7-4.

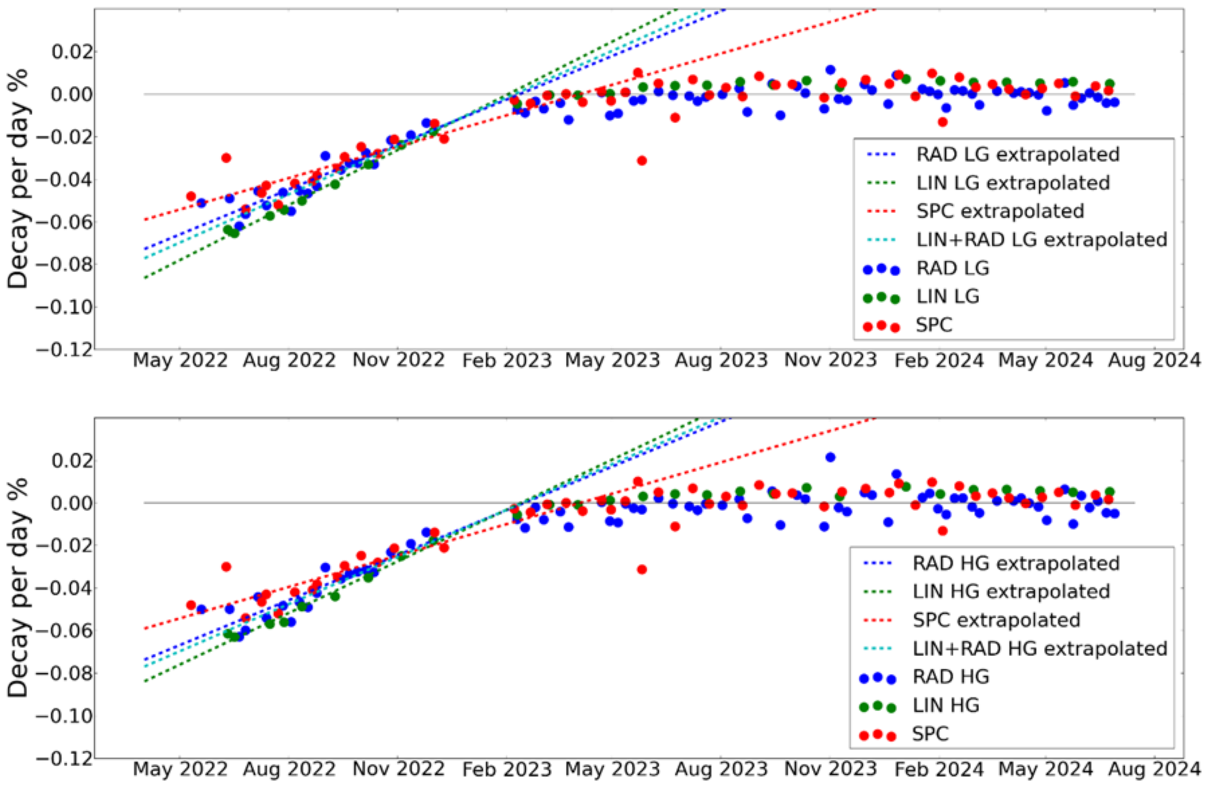


Figure 7-3 Decay per day from Lamp (RAD), Linearity (LIN) and Spectral (SPC) measurements for low gain (top) and high gain (bottom)

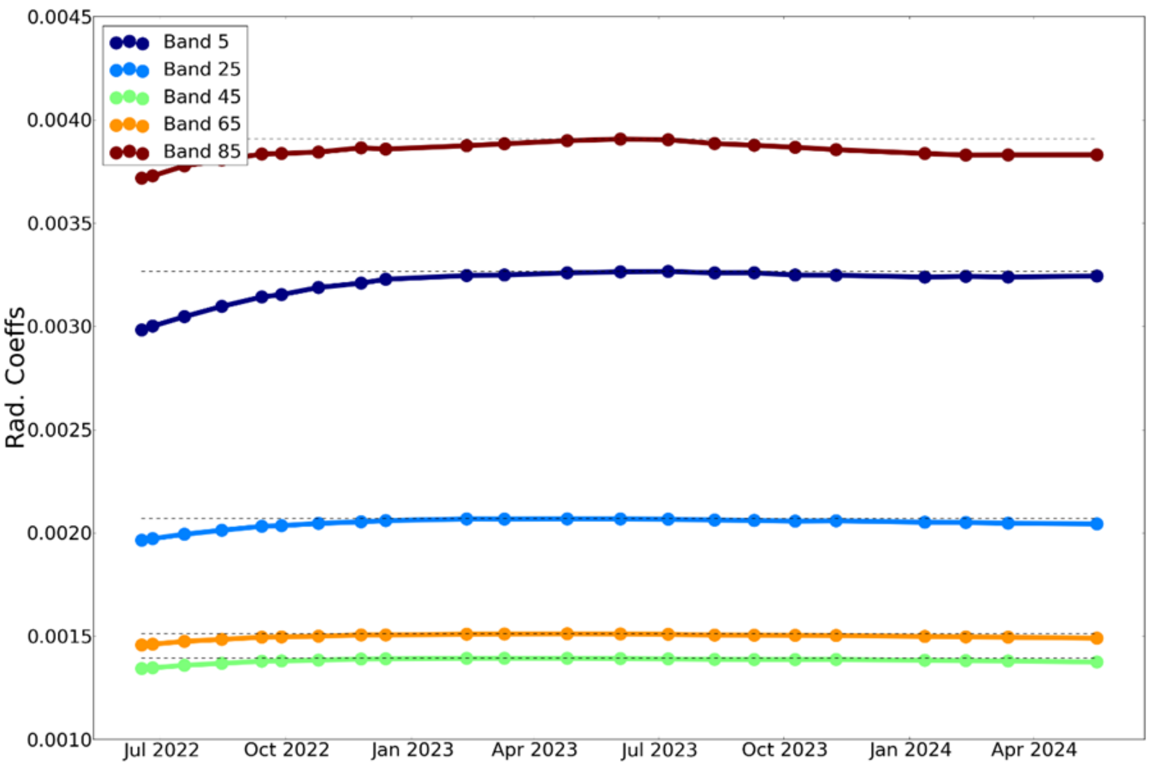


Figure 7-4 Average percentage change in the VNIR radiometric coefficients for five selected bands since launch

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	01.04.2024 to 30.06.2024	
	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

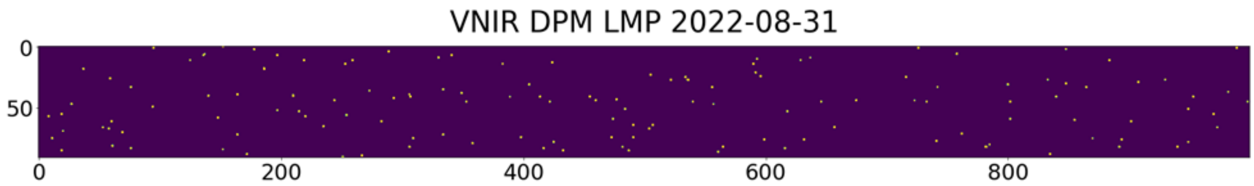


Figure 7-5 VNIR Dead Pixel Mask

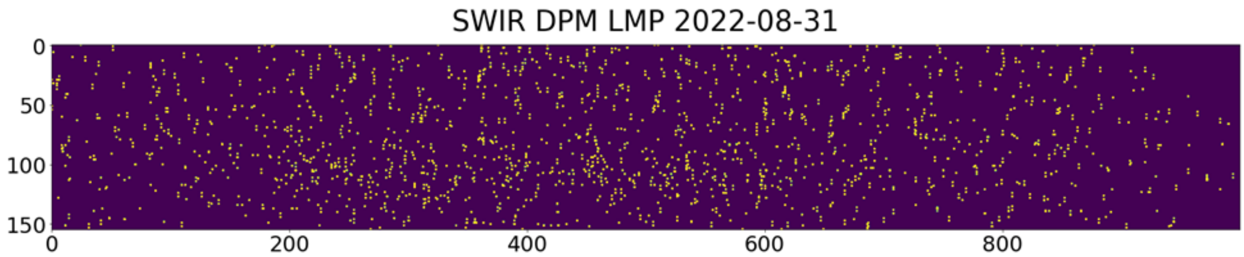


Figure 7-6 SWIR Dead Pixel Mask

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	01.04.2024 to 30.06.2024	
	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 is summarized as follows:

- During the reporting period, 6 spectral calibration measurements were made which took place on: 13.04.2024, 27.04.2024, 11.05.2024, 25.05.2024, 11.06.2024 and 22.06.2024.

- 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 902.2 – 2445.5 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 <0.2 nm change from the VNIR sensor and <0.2 nm change in SWIR (Figure 7-8 shows deviations with respect to the present spectral calibration). All changes were below 0.5 nm between measurements for VNIR and 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 0.18% across all pixels during the reporting period. A slightly larger change was reported in the previous quarter (0.22%). Although small, the monitoring of this behavior should be continued in the next reporting period.

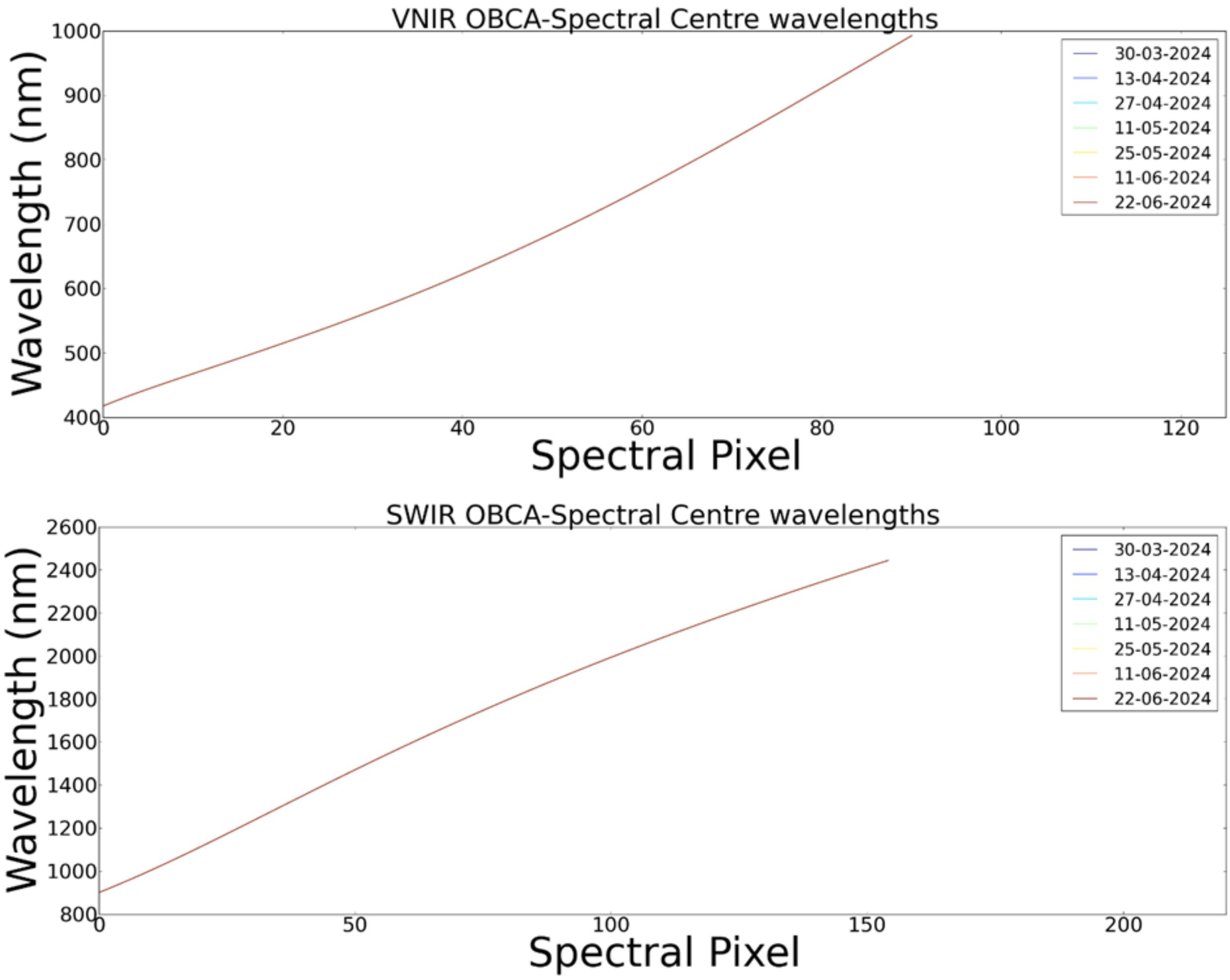
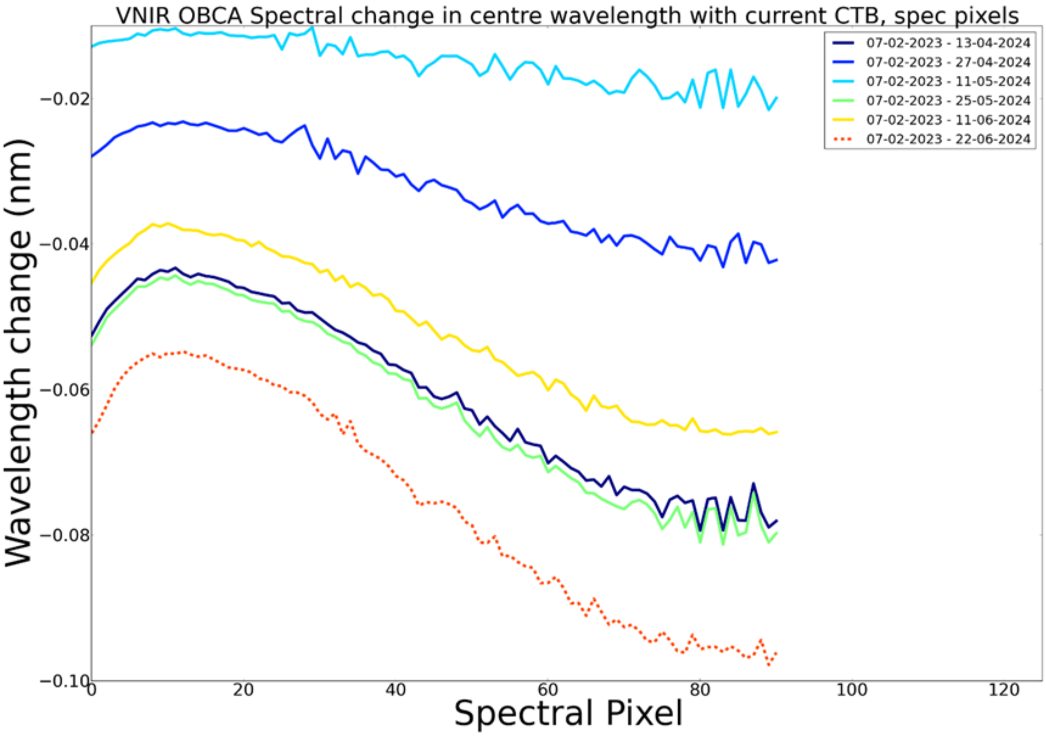


Figure 7-7 VNIR (top) and SWIR (bottom) center wavelength in nm



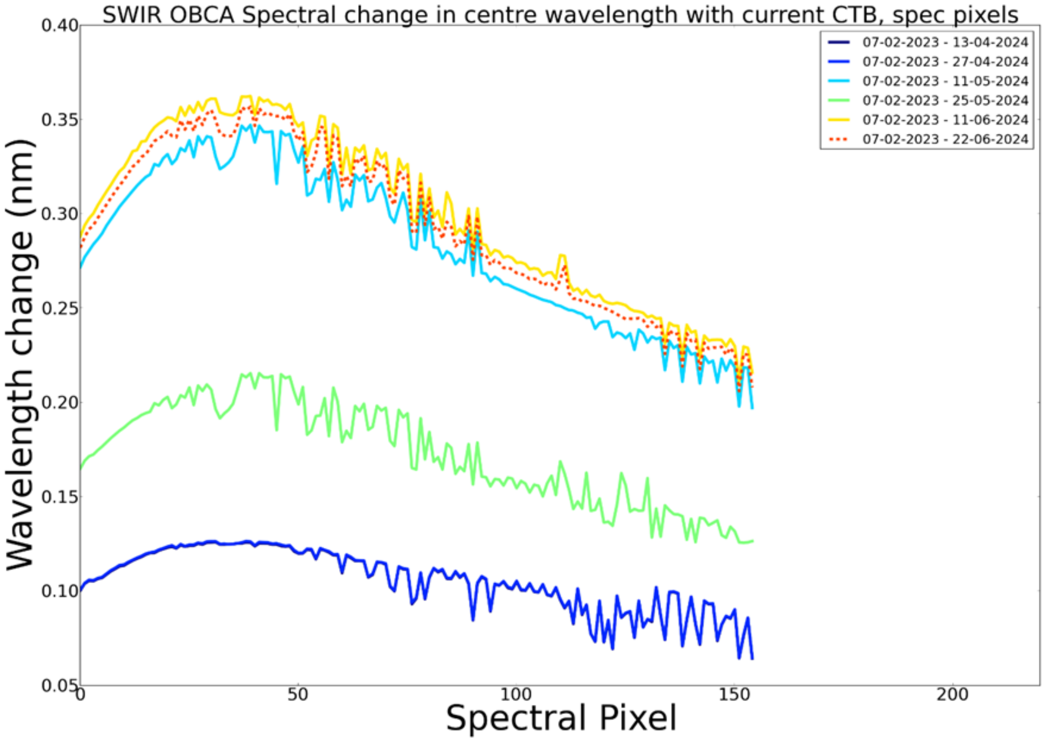
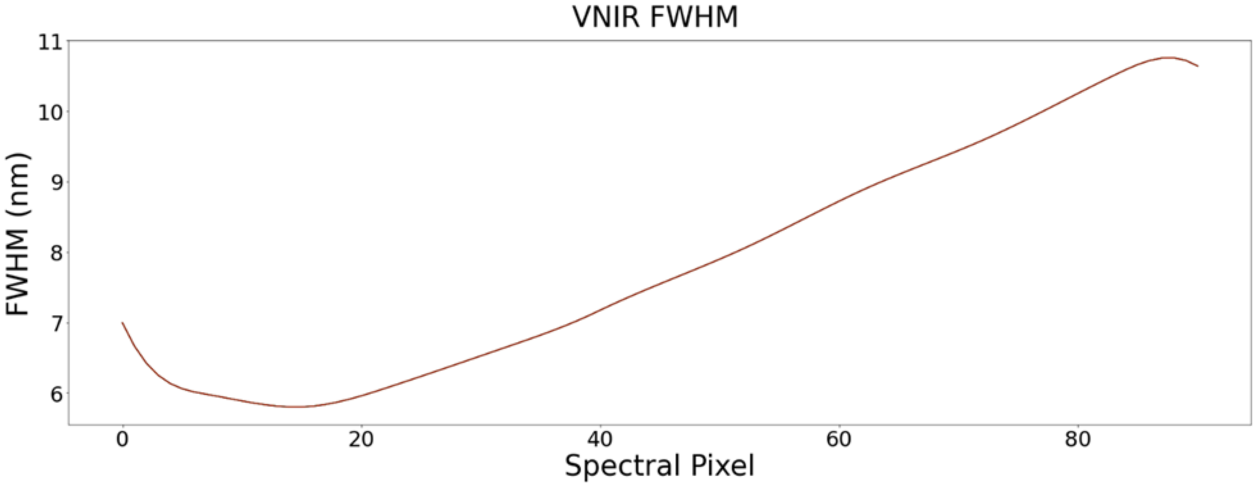


Figure 7-8 Change in center wavelength per spectral pixel for VNIR (top) and SWIR (bottom) with respect to current spectral calibration table in use.



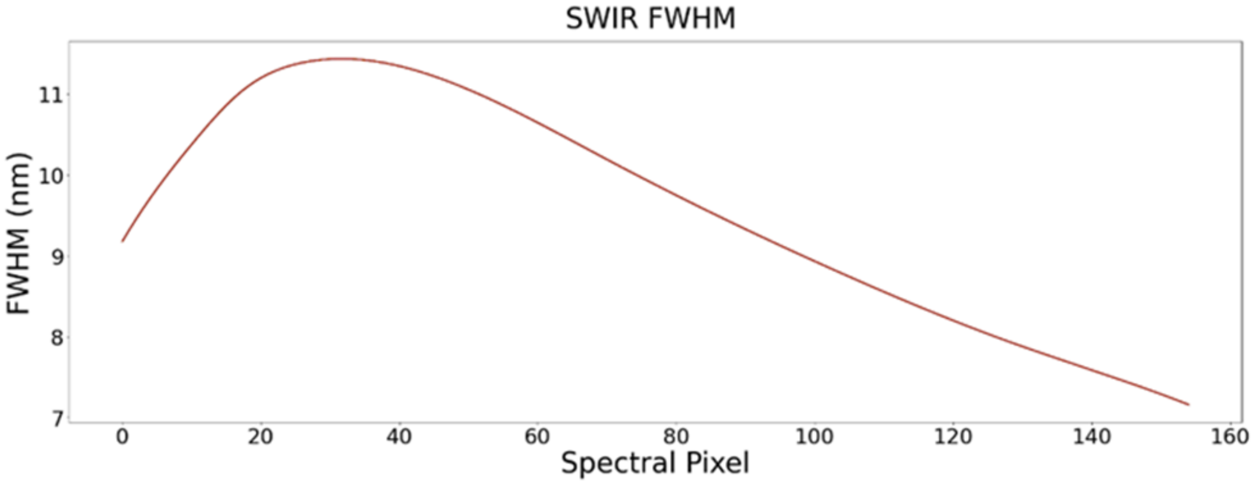


Figure 7-9 VNIR (top) and SWIR (bottom) FWHM in nm

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

In the last reporting period (01.01.-31.03.2024, Quarter 1 2024), all of the old spectral calibration tables were updated due to a change in MIP which led to the calculation of new water LUTs to fix the spectral noise below 500 nm in water spectra (new processor version V04.01.00): however, the contents of the spectral calibration tables did not change with the updated versions. Upon further investigation, it was found that there were small differences between two of the old and new tables. Small changes were seen for the calibration table dated 02.04.2022 when changing from V01.00.01 to V04.01.00: this was due to the fact that backdated inflight tables were used in the calculation of the new centre wavelengths rather than the preflight tables. For the calibration table dated 25.06.2022, small changes were also seen when changing from V02.00.00 to V04.01.00: this was because of a small smile shift which was corrected in the newer version. The changes in these two cases were small and no further action was required.

7.5.3 Radiometric Calibration

Category	01.04.2024 to 30.06.2024	
	Number of Archived Observations	Size (in GB)
Total	19	103
Deep Space	3	3.9
Rel. Radiometric	12	46.8
Abs. Radiometric	1	1.3
Linearity	3	51

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.

Both sensors feature two gain settings each. VNIR applies a quantization of 13 bits using a pixel-individual automatic gain switching, where the low gain value is automatically selected, if the signal exceeds a defined threshold. SWIR applies a fixed gain setting, where bands below 1980 nm take the low gain value and bands above 1980 nm take the high gain value.

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, 1 Absolute Radiometric calibration measurements was obtained. This took place on: 17.05.2024.

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 -0.212% to offset the increase in absolute signal (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, 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.

- Starting from April 2024, Absolute Radiometric calibration measurements are now 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.

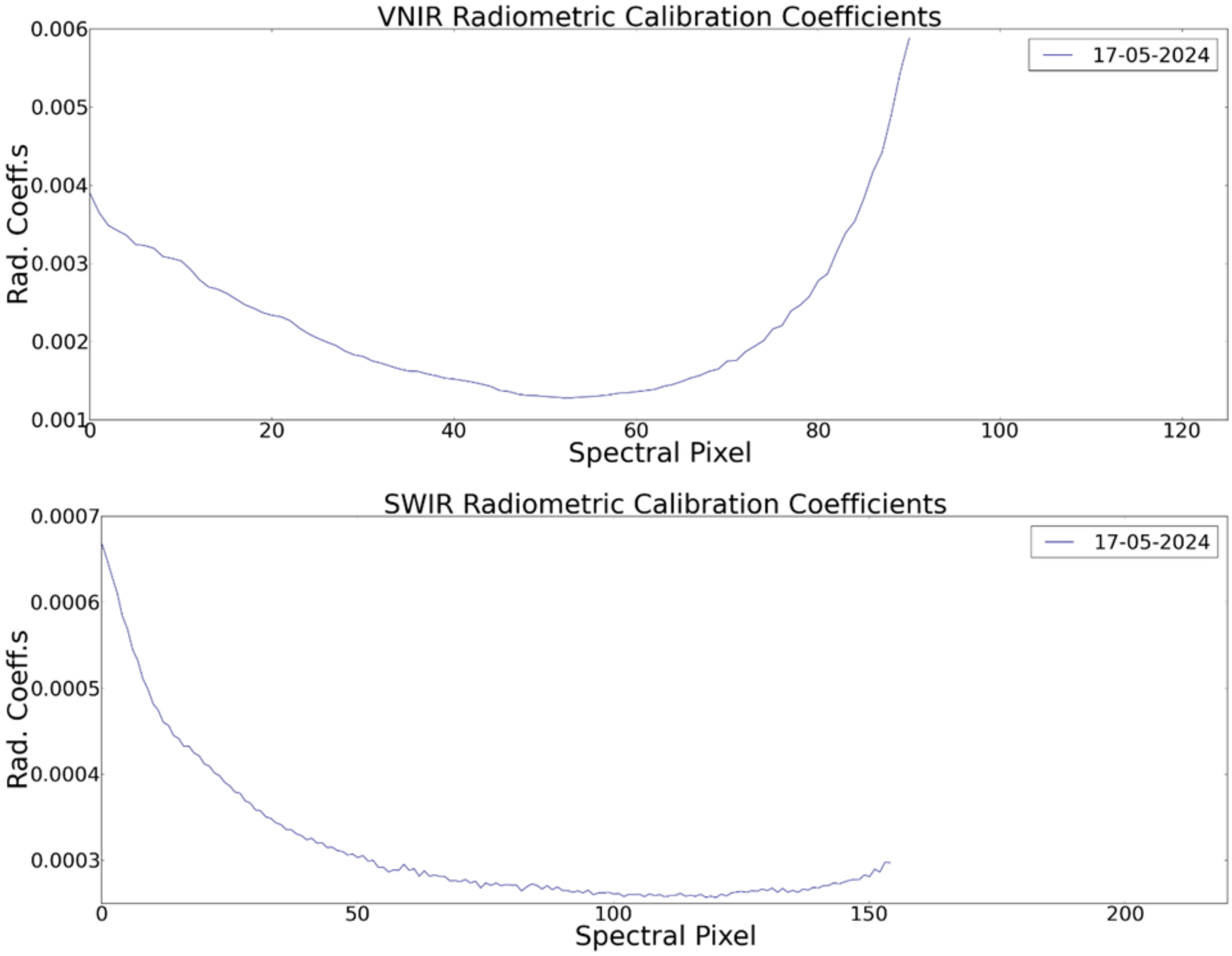
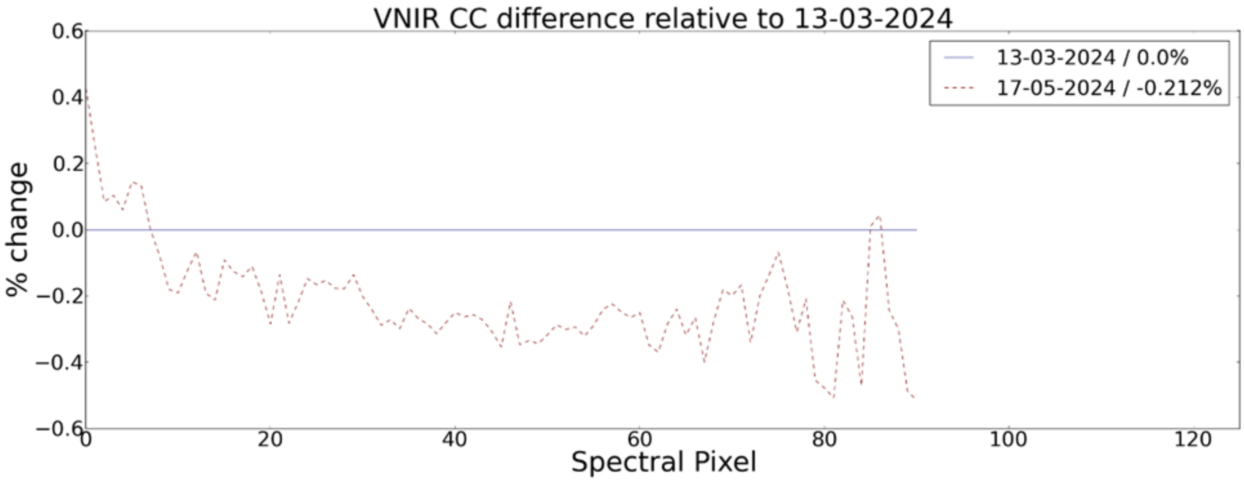


Figure 7-10 VNIR (top) and SWIR (bottom) calibration coefficient in $mW/cm^2/sr/\mu m$



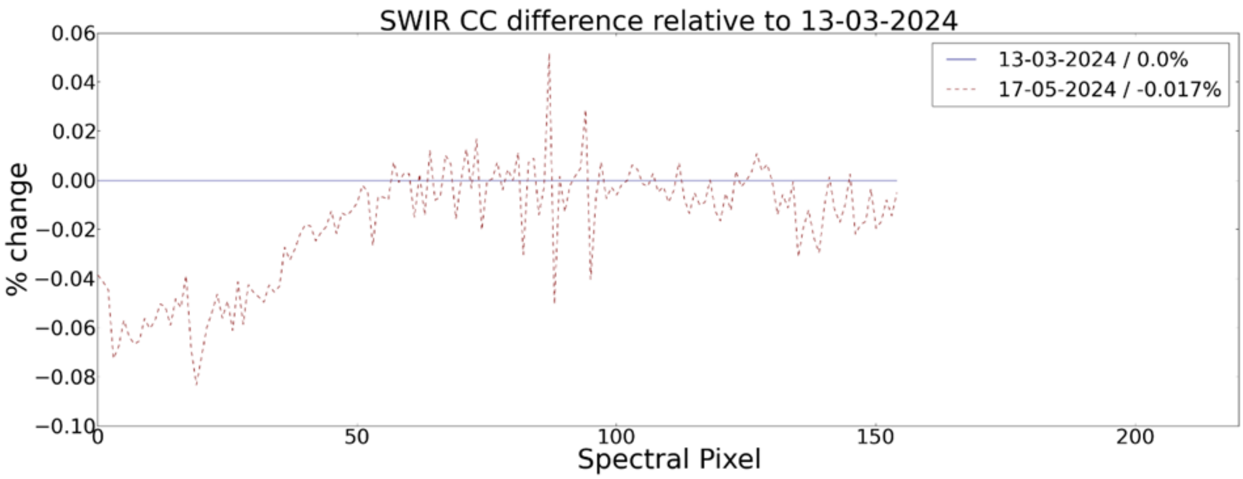


Figure 7-11 Percentage change in VNIR Calibration Coefficients (top) and SWIR Calibration Coefficients (bottom)

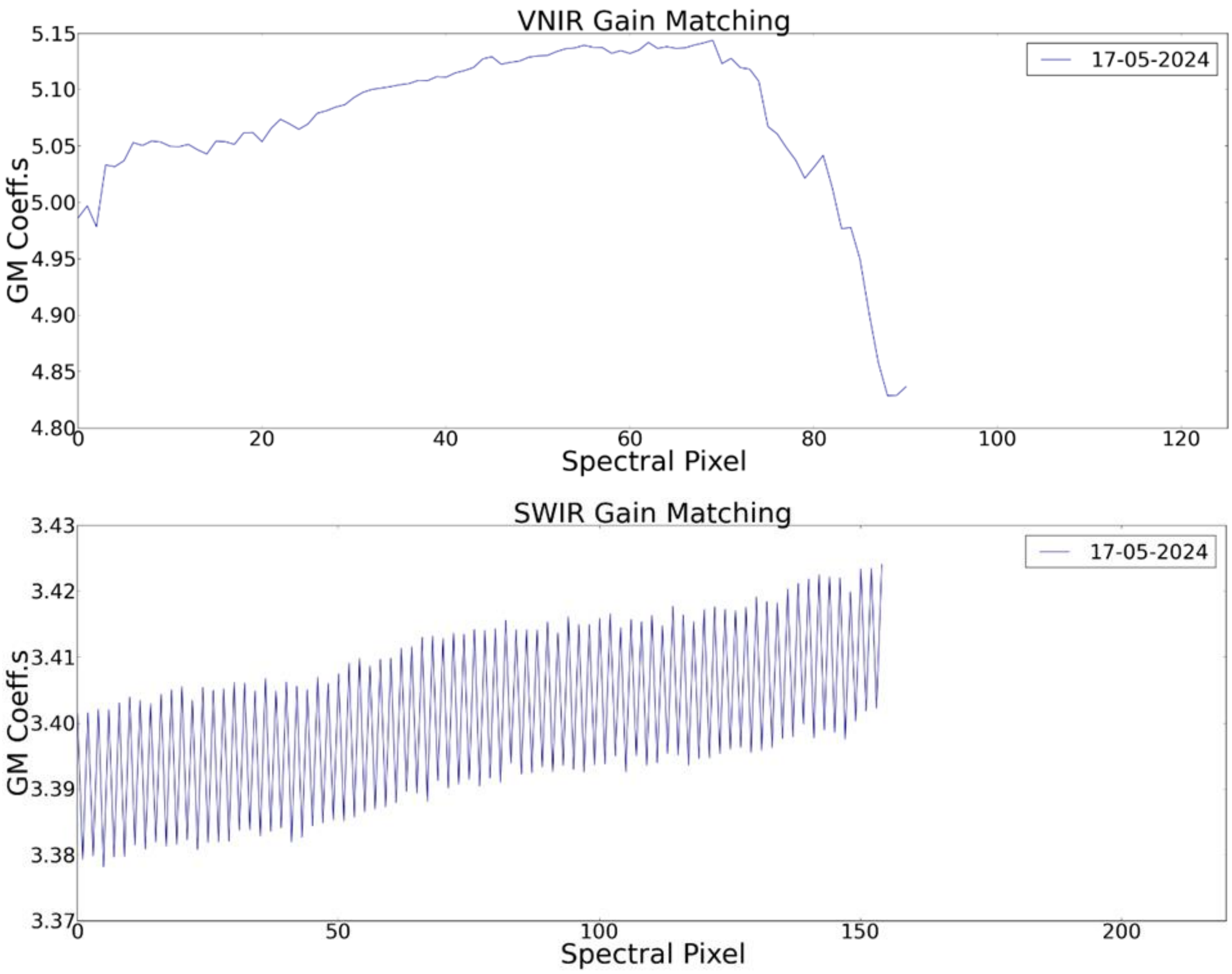


Figure 7-12 VNIR (top) and SWIR (bottom) gain matching calibration coefficients

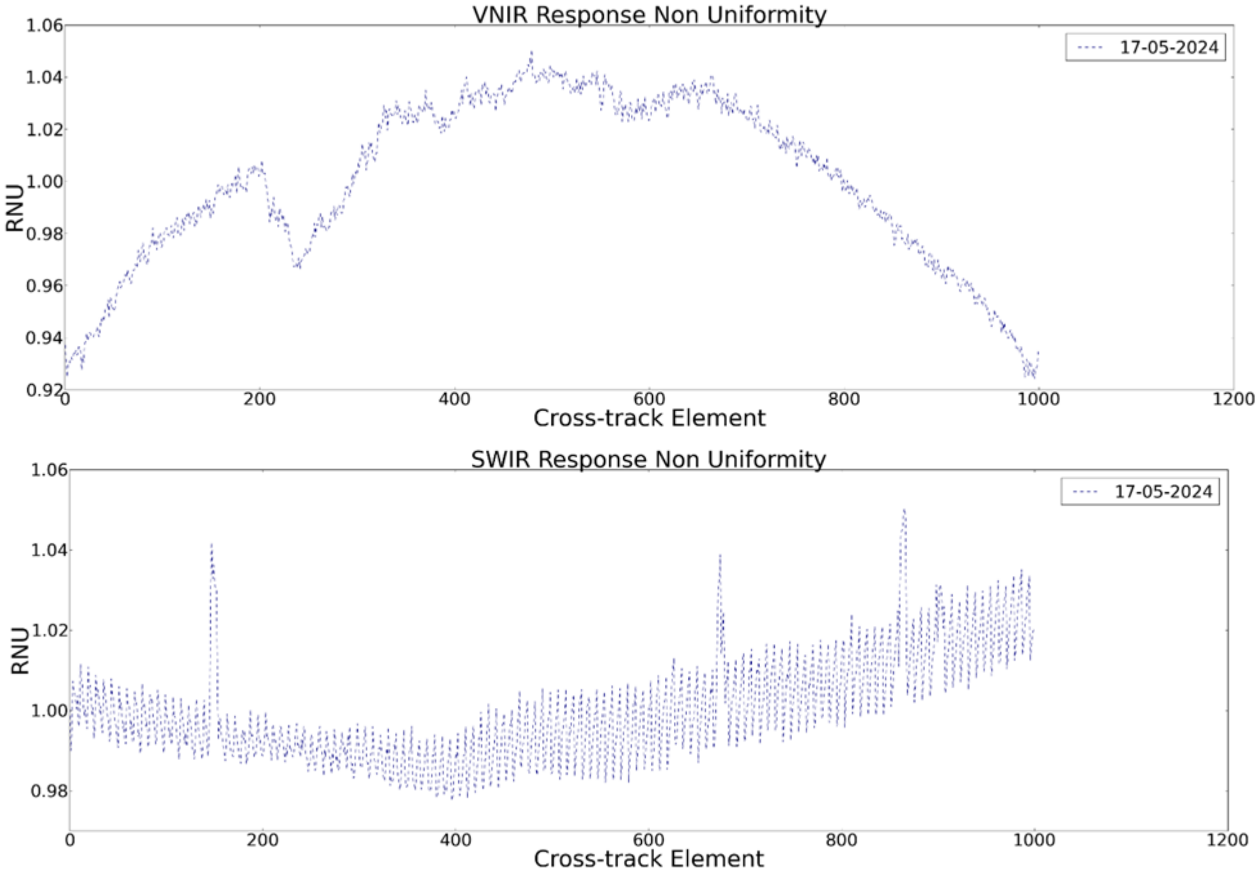


Figure 7-13 VNIR (top) and SWIR (bottom) response non-uniformity coefficients

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 solar reference spectrum (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: SNR greater than 500 at 495 nm in VNIR for the solar reference spectrum value; and SNR greater than 150 at 2200 nm in SWIR for the reference spectrum.

For the VNIR sensor, SNR is computed from the linearity calibration measurement. SNR values are shown as a contour map with the solar reference spectrum (30% reflectance, 30° sun incidence angle, 21 km visibility, target 500 m above sea level) as a blue line. Contour lines with SNR values of 150 and 500 are also shown in black. A similar plot for the low gain mode including the position of the requirement [HIS-POSR-0010] which is marked with a black cross.

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 solar reference spectrum (30% reflectance, 30° sun incidence angle, 21 km visibility, target 500 m above sea level) as a blue line and the position of the requirement [HIS-POSR-0010] is marked with a black cross. Contour lines with SNR values of 150 and 500 are also shown in black.

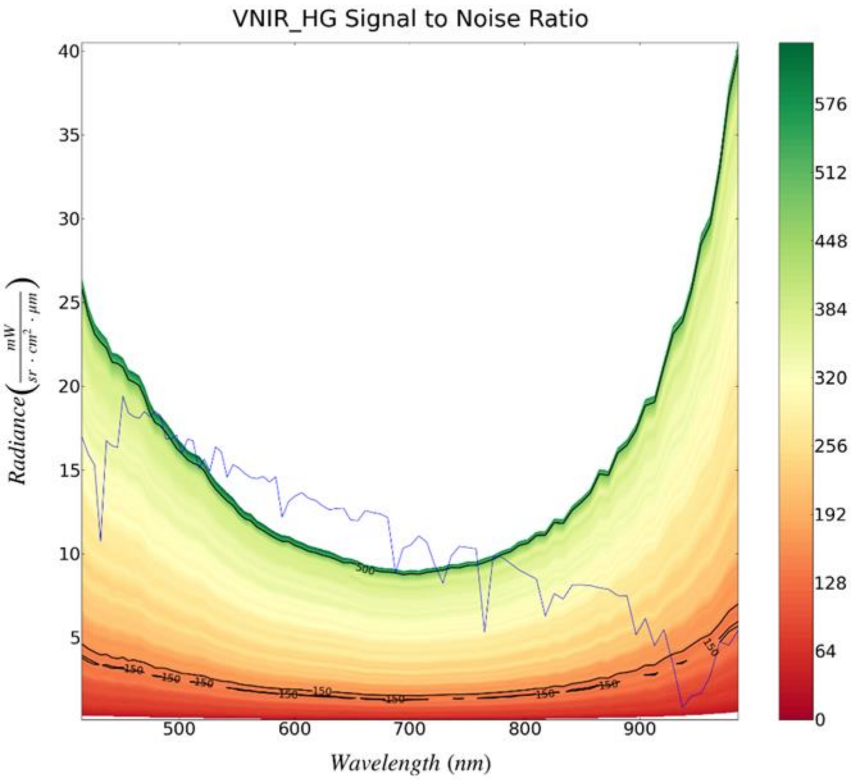


Figure 7-14 SNR contour map for VNIR high gain from the LED linearity observations observed on 23.06.2024. The solar reference spectrum is shown with a blue line. Contour lines with SNR values of 150 and 500 are also shown in black.

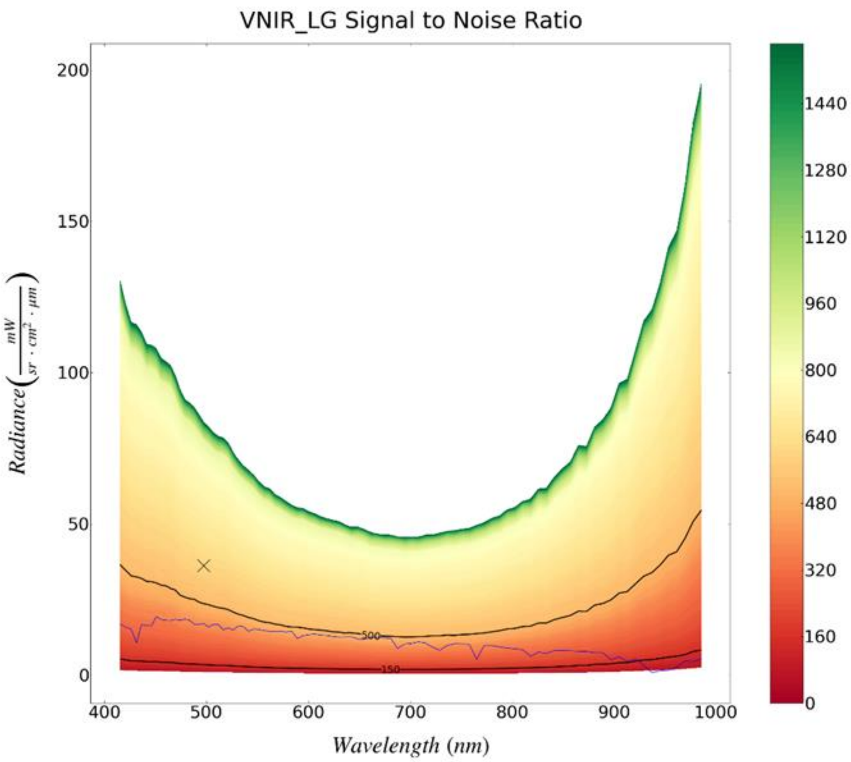


Figure 7-15 SNR contour map for VNIR low gain from the LED linearity observations observed on 23.06.2024. The solar reference spectrum is shown with a blue line and the position of the requirement is marked on the reference spectrum with a black cross. Contour lines with SNR values of 150 and 500 are also shown in black.

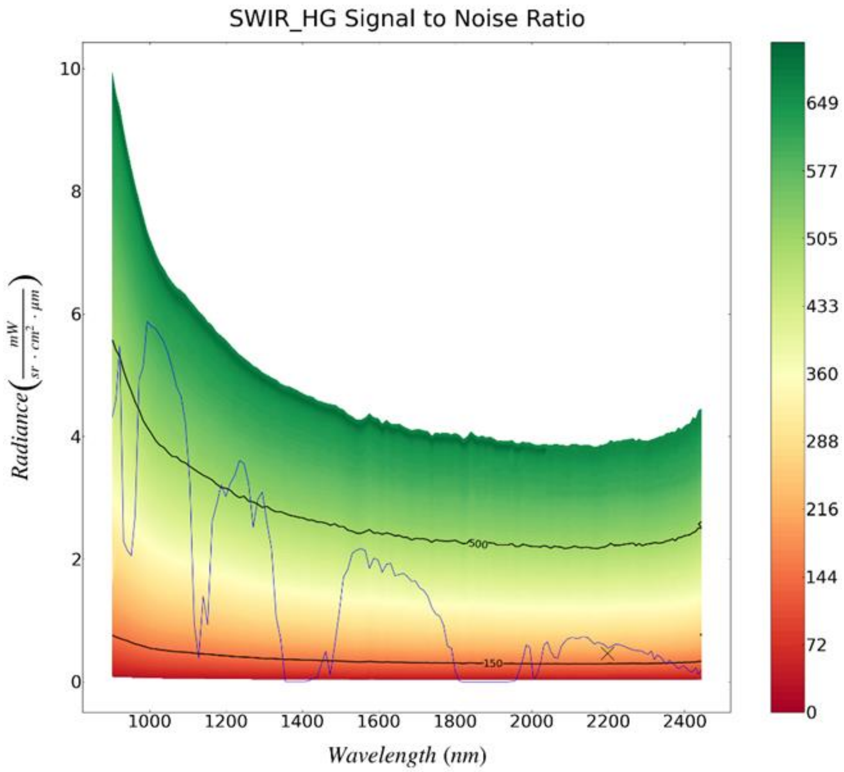


Figure 7-16 SNR contour map for SWIR high gain from the LED linearity observations observed on 23.06.2024. The solar reference spectrum is shown with a blue line and the position of the requirement is marked on the reference spectrum with a black cross. Contour lines with SNR values of 150 and 500 are also shown in black.

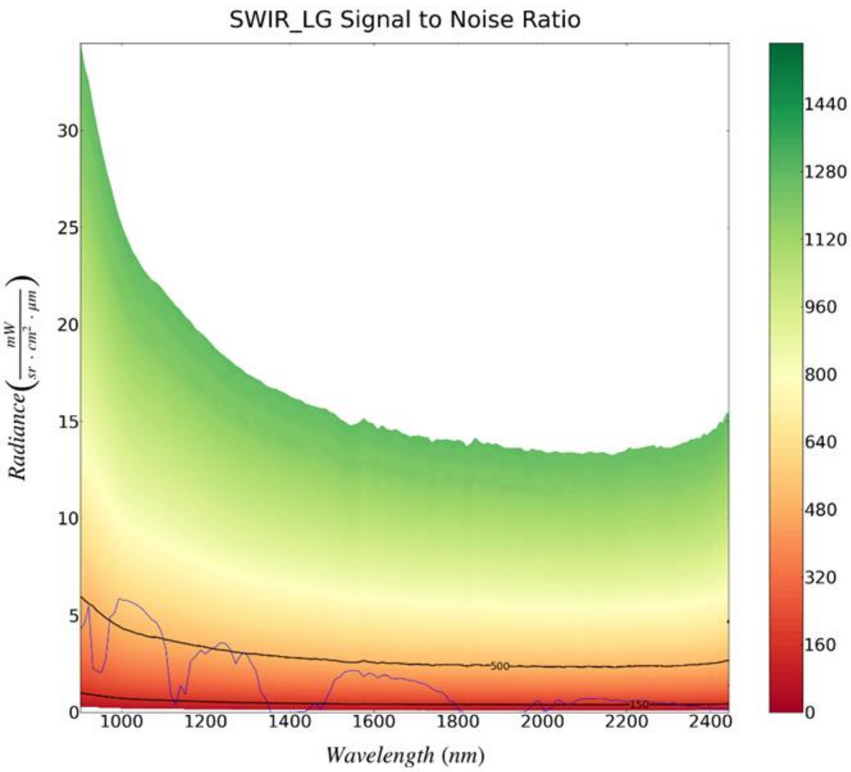


Figure 7-17 SNR contour map for SWIR low gain from the LED linearity observations observed on 23.06.2024. The solar reference spectrum is shown with a blue line. Contour lines with SNR values of 150 and 500 are also shown in black.

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-20221125T000000Z_V040002_20230201T090613Z	CTB_RAD	25.06.2024	25.11.2022	13.12.2022	DIMS
ENMAP01-CTB_RAD-20230201T000000Z_V030000_20230217T143611Z	CTB_RAD	25.06.2024	01.02.2023	08.02.2023	DIMS
ENMAP01-CTB_RAD-20240529T000000Z_V040100_20240521T081827Z	CTB_RAD	21.05.2024	29.05.2024	-	DIMS
ENMAP01-REF_SUN-20240529T000000Z_V040100_20240521T081827Z	REF_SUN	21.05.2024	29.05.2024	-	DIMS

Table 7-9 Generated radiometric calibration tables

One new radiometric calibration table was produced in this reporting period based on the latest sun calibration measurement. Two further tables were produced in this quarter based on a set of unprocessible datatakes from 07.02.2023. After analyzing these datatakes, it was found that they used the wrong calibration table resulting from an error in the validity start date of the table from November 2022. This error was corrected and a new table was uploaded to DIMS (ENMAP01-CTB_RAD-20221125T000000Z_V040002_20230201T090613Z). Furthermore, as the unprocessible datatakes were acquired just after the outage in 2022-2023, it was decided to backdate the radiometric calibration table from 08.02.2023 to 01.02.2023 by uploading a duplicate copy with an earlier validity start date (ENMAP01-CTB_RAD-20230201T000000Z_V030000_20230217T143611Z). In this way, the affected datatakes would use the calibration table from just after the outage (and only one day after the affected datatakes were accquired) rather than the table from before the outage.

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 (2024-04-01 and 2024-06-30), 1713 datatakes with a total of 18226 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), 13% of the “reduced quality” ratings and over 25% of the “low quality” ratings can be related to low Sun angles / night time acquisitions. This increase can be explained as more acquisitions were taken in the northern hemisphere where during winter unfavourable illumination conditions apply.

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), 7% of the “reduced quality” ratings and 9% of the “low quality” ratings can be related to low Sun angles / night time acquisitions. This decrease w.r.t. Q1 2024 can be explained as more acquisitions were taken in the northern hemisphere where during spring and summer illumination conditions are again favourable. In addition, the “low qualityAtmosphere” rating can be further related to high cloud cover (56% of the low qualityAtmosphere tiles) and the unavailability of enough DDV pixels (72%) (see Table 7-16). Consequently, the rating is absolutely reasonable and can be explained.

Parameter	Value	Percentage	Number of tiles
overallQuality	Nominal	98,1%	17878
	Reduced	<1%	24
	Low	1,8%	327

Table 7-11 Overall quality rating statistics

Parameter	Number of tiles	Sub-Parameter	Number of tiles
overallQuality = Low	327		
		Thereof with SZA > 70°	327

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

Parameter	Number of tiles	Sub-Parameter	Number of tiles
overallQuality = Reduced	21		
		Thereof with qualityVNIR nominal	5
		Thereof with qualitySWIR nominal	16
overallQuality = Low	327		
		Thereof with qualityVNIR nominal or reduced	67
		Thereof with qualitySWIR nominal or reduced	327

Table 7-13 Reduced and low quality rating statistics

Parameter	Value	Percentage
QualityAtmosphere	Nominal	40%
	Reduced	12%
	Low	48%

Table 7-14 QualityAtmosphere rating statistics

Parameter	Number of tiles	Sub-Parameter	Number of tiles
overallAtmosphere = Reduced	2227		
		Thereof with SZA > 60°	175
		Thereof with SZA > 70°	37
		Thereof with SZA > 80°	12
overallAtmosphere = Low	8759		
		Thereof with SZA > 60°	803
		Thereof with SZA > 70°	476
		Thereof with SZA > 80°	361

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

Parameter	Number of tiles	Sub-Parameter	Number of tiles
overallAtmosphere = Low	8759		
		Thereof with Cloud Cover > 66%	4891
		Thereof with DDV warnings	6281

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 16380 tiles, with 16207 suitable for analysis):

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

Band Cross-track element

~~19~~	~~187~~
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~~.

NOTE: due to the change in SWIR band configuration within the previous period Q3 (see EN-GS-RPT-1803 Issue 5), the band index from band 45 till 75 did change by +1 (with bands 45, 74 & 75 newly added). Thus, in the following, the new band numbers are given, while the colour index is adjusted in order to account for real changes.

Band	Cross-track element	Band	Cross-track element	Band	Cross-track element
~~1~~	~~817~~	48	511	96	341, 819
2	235, 286, 593, 673	50	311, 344, 395	100	513
4	362, 363, 418	~~51~~	~~155~~	101	318
5	687	53	97, 98	106	107
7	910	54	602, 941	107	265, 764
8	801	56	221, 965	108	886
8	124	58	632, 922	111	315
11	715	59	89, 90	118	837
14	29, 684	61	312		
16	535	63	123		
19	84	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 the EN-GS-RPT-1702 Radiometric Calibration Report, 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
DeadPixelsVNIR	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	91%
	> 0 per mille	9.5%
	> 10 per mille	1.7%

Table 7-19 Saturation statistics, VNIR

Parameter	Value (per mille of scene)	Percentage of tiles
SaturationCrosstalkSWIR	0	92%
	> 0 per mille	8.0%
	> 10 per mille	0.4%

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	5.6%
	> 100	1.8%
	> 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	5.5%
	> 100	2.2%

	> 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) relative to the CTB_SPC (Figure 7-19) 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.

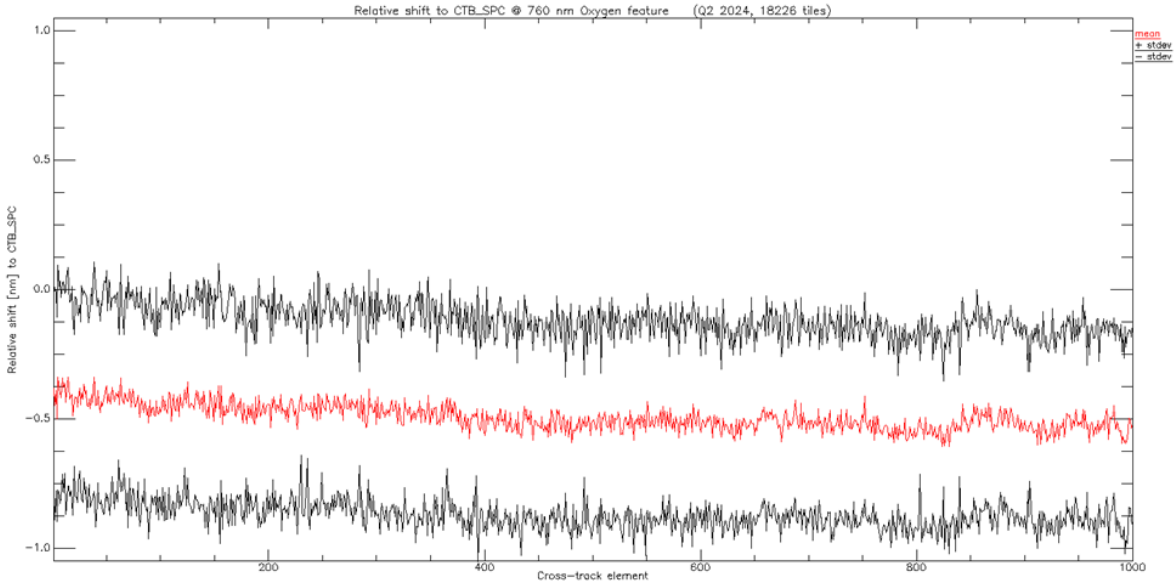


Figure 7-18 VNIR estimated spectral shift at 760 nm w.r.t the valid spectral calibration table (CTB_SPC, shown in Figure 2), and relative spectral stability expressed at 1 sigma (Q2 2024, 18226 tiles)

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 7-19).

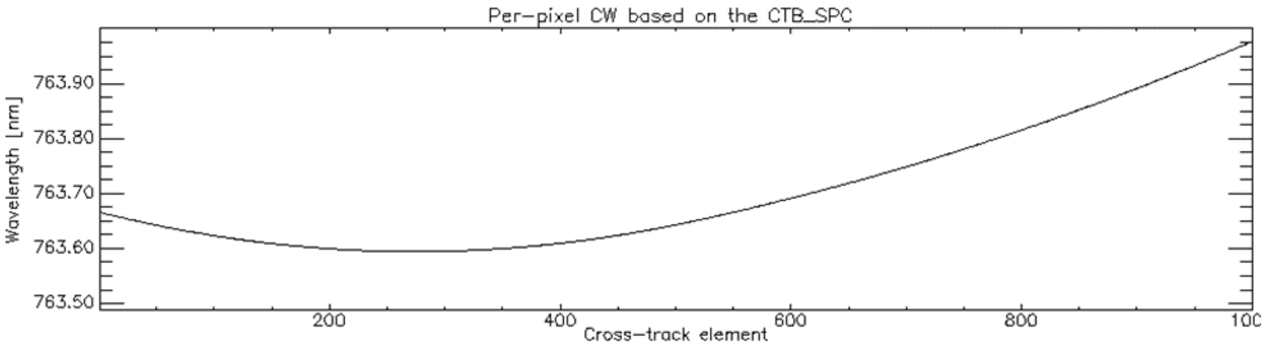


Figure 7-19 Center wavelengths per cross-track pixel based on the spectral calibration table (VNIR band 62) in the calibration table (CTB_SPC).

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. Note that for Q2 2024, the spread is also slightly increased in the SWIR w.r.t. Q1 2024, with the mean and median of the sdtev of 0.6 nm (1 sigma) being the same as Q1. This is very likely an effect of more clutter within the acquire datatakes, as also the histograms generated with additional clutter removal are highly similar to Q1 2024.

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 ~0.6 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.

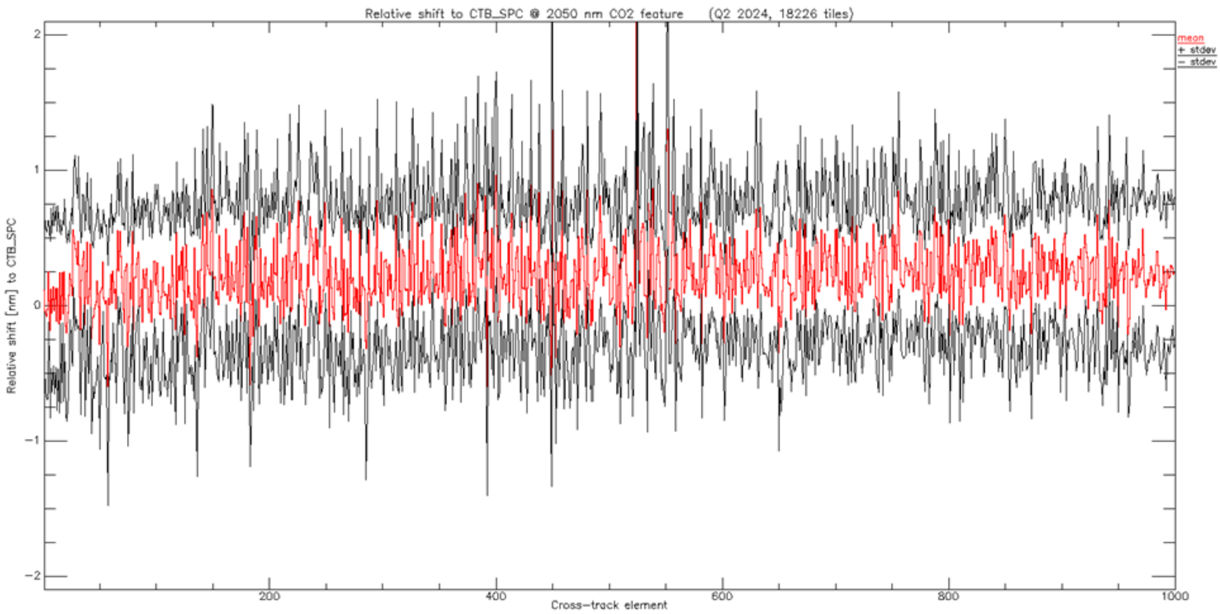


Figure 7-20 SWIR estimated spectral shift at 2050 nm w.r.t the valid spectral calibration table (CTB_SPC, shown below), and relative spectral stability expressed at 1 sigma (Q2 2024, 18226 tiles)

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).

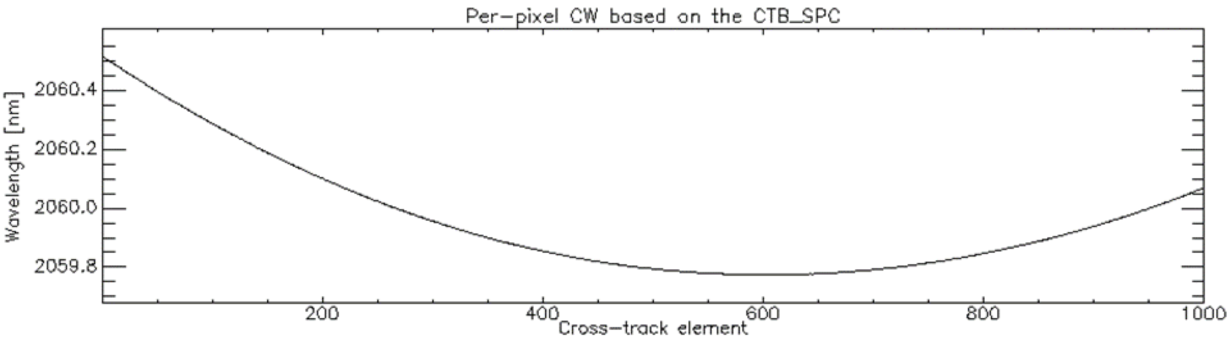


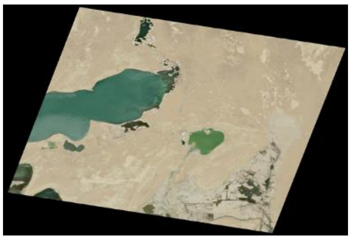
Figure 7-21 Center wavelengths per cross-track pixel based on the spectral calibration table (SWIR band 86).

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

Validated CTB	ENMAP01-CTB_RAD-20240529T000000Z_V040100_202405
Datatake used	ENMAP01-____L0-DT0000075638_20240529_005  Figure 7-22 Datatake used (Kazakhstan)

Summary of result	New CTB_RAD confirmed
	• VNIR: for the given scene,
	  • relative changes to P29 are similar as between periods before (mainly below 0.3%)
	  • for given scene, the absolute change is between -0.04 and +0.03 in TOA_rad [mW sr-1 cm-2 µm-1] with a slight recovery in almost all bands
	  • for the given scene, no VNIR fringing is visible
	  • as before, for bands above ~450 nm differences are slightly higher at center than towards edges of detector, with the stable “fingerprint” showing up.
	• SWIR: for the given scene:
	  • relative and absolute change to P29 are very small (below 0.8%), similar to the previous period
	  • 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	

7.6.3 Level 1C

This report covers the timeframe between 01.04.2024 and 30.06.2024. No geometric calibration was performed during this period.

In the timeframe of this report, 1713 datatakes have been acquired. In 1240 of those datatakes (~72 %), enough GCPs and ICPs 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 7-23.

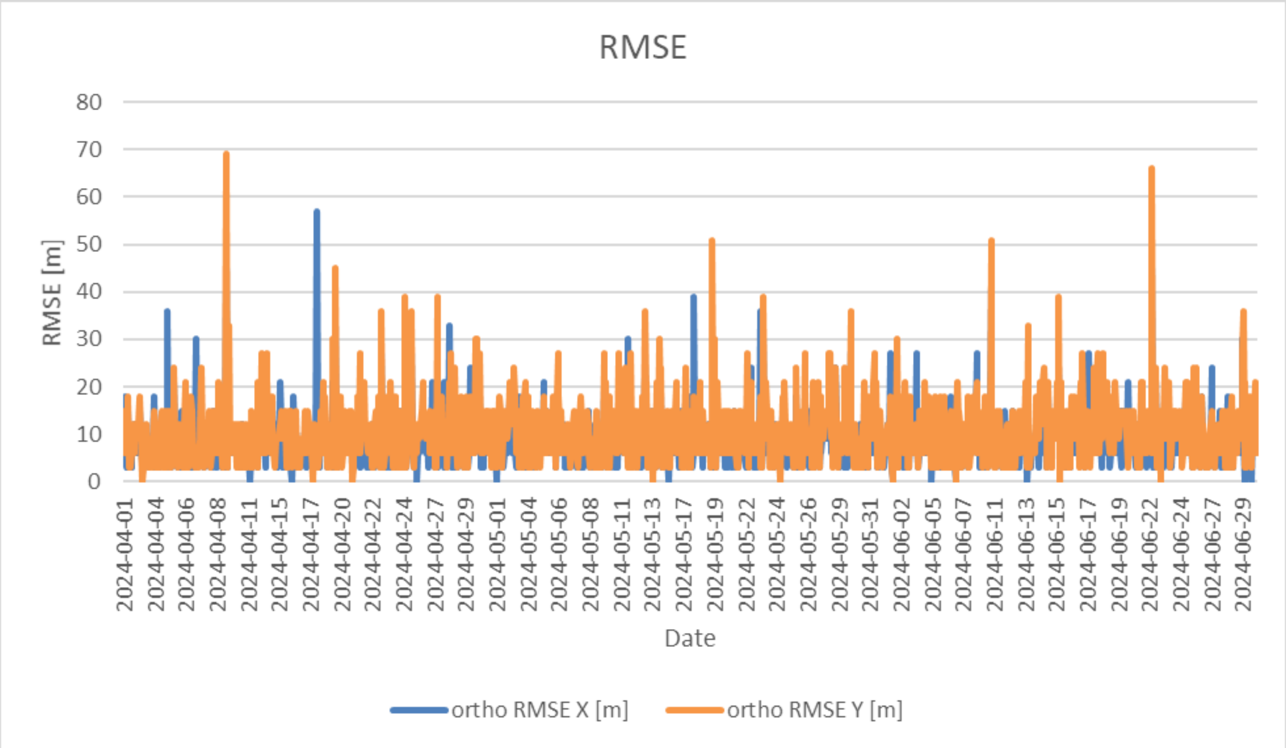


Figure 7-23 Assessment of RMSE values, calculated based on found ICPs, for all datatakes where ICP could be found

In x-direction, 9 datatakes (~0.7%) had an RMSE value above 30 m (1 GSD), whereas in y-direction, 16 datatakes (~1.3%) 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 8.36 m in x-direction and 10.56 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. Around May 11 2024, severe magnetic storms occurred. However, no significant effects on the geometric accuracy could be detected.

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 -2 m in x direction with a standard deviation of approximately 21 m and -43 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 7-24) 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 01.04.2024 to 30.06.2024. A random sample of 490 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.

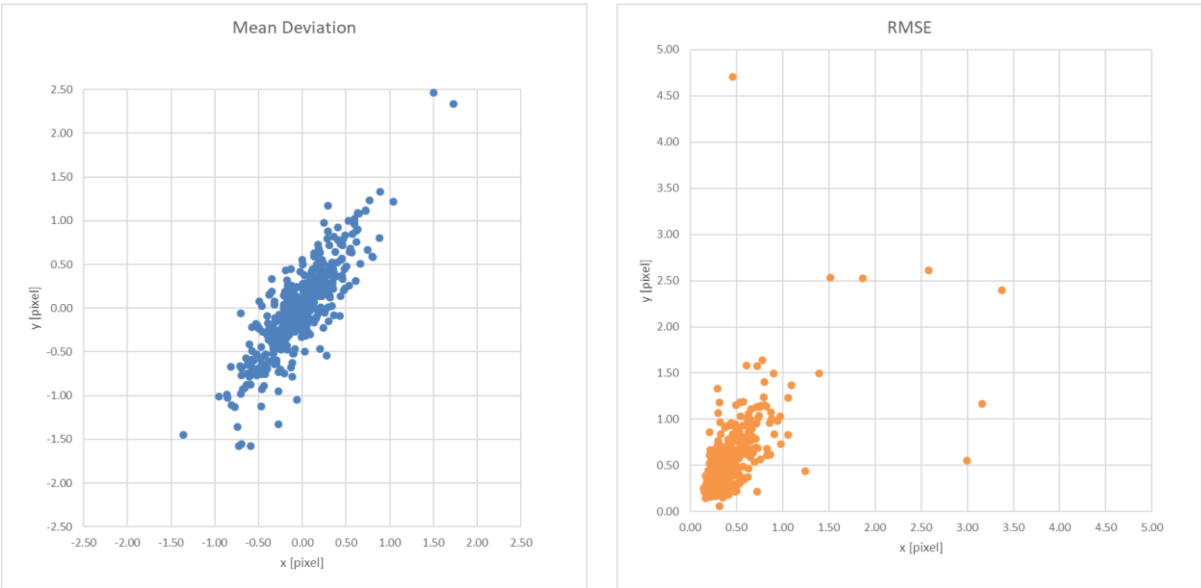


Figure 7-24 Mean deviation of EnMAP L1C products in pixel (left). RMSE value for EnMAP L1C products in pixel (right)

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 490 L1C tiles are -0.02 and 0.01 pixel in mean deviation with a standard deviation of 0.34 and 0.48 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 7-26).

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 7-25).

This report covers EnMAP data from 01.04.2024 to 30.06.2024. A random sample of 494 L1C tiles was selected based on visual inspection of the catalogue quicklooks (e.g. to avoid cloudy images).

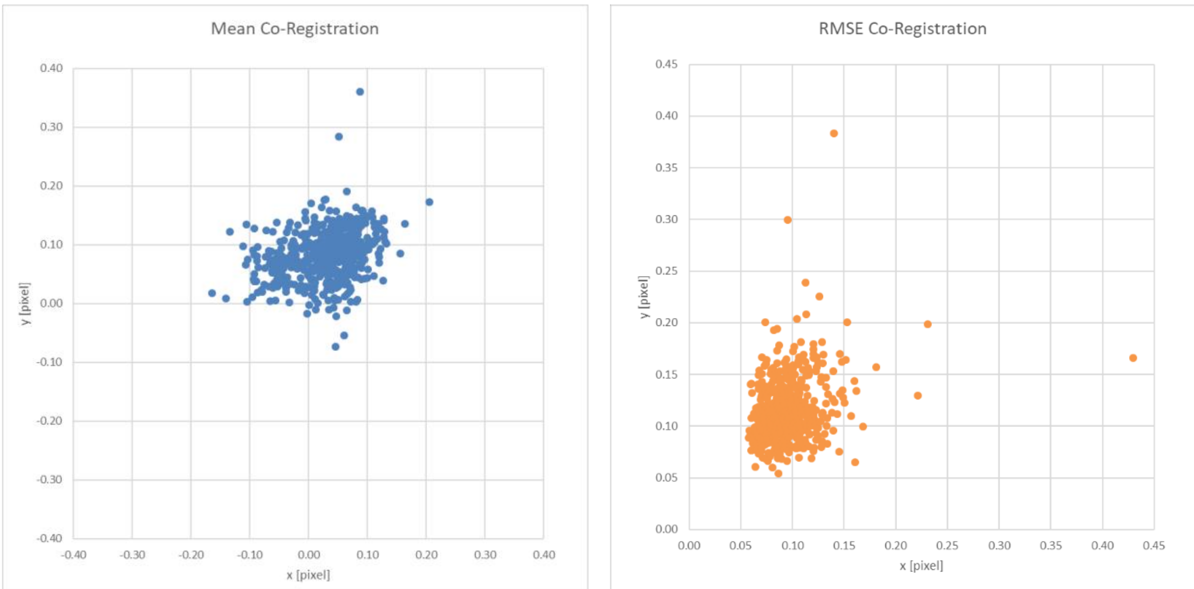


Figure 7-25 Mean deviation in pixel between VNIR and SWIR data of EnMAP L1C products (left). RMSE in pixel between VNIR and SWIR data of EnMAP L1C Products (right)

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 0.03 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 7-26.

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 0.03 pixel in x-direction with a standard deviation of 0.05 pixel and 0.09 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.

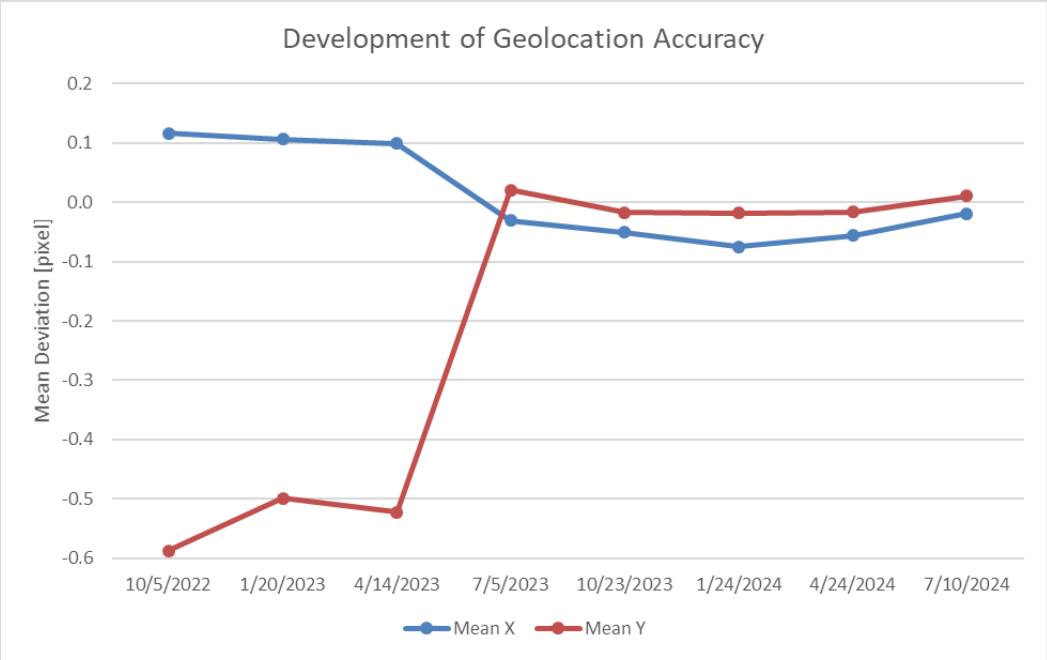
7.6.3.3 **Development of geometric performance**

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 7-25 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 7-25 Improvement of geometric performance

Figure 7-26 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.



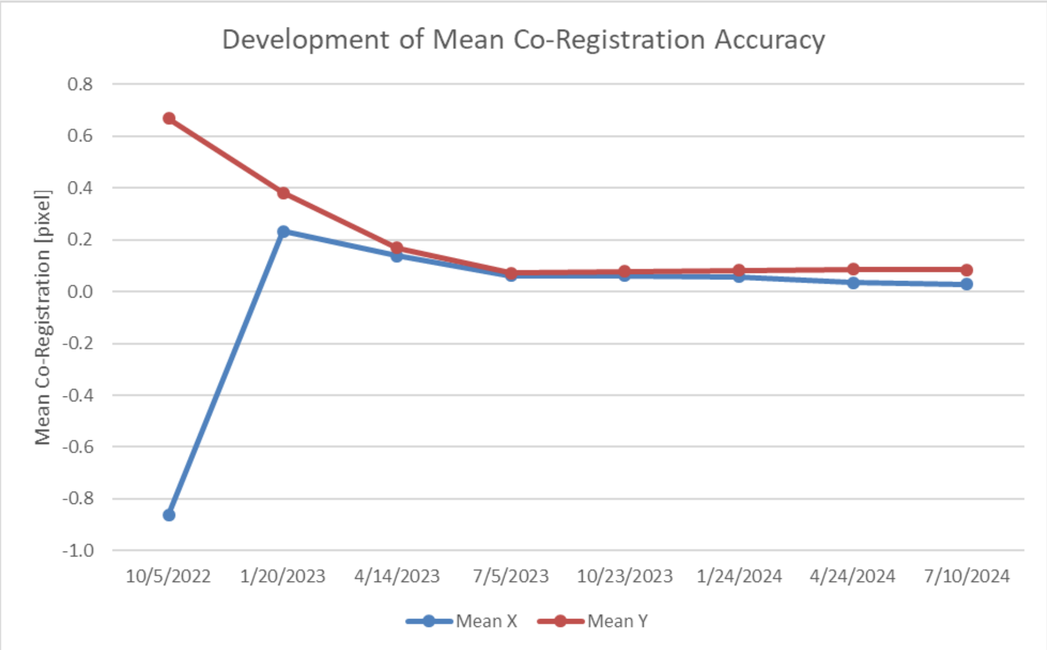


Figure 7-26 Development of co-registration accuracy based on the previous geometric QC reports

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
72210	2	Lake Hume	Water mode, water type "clear"	Cirrus	Nominal
73100	29	Lake Constance, GER	Water mode, water type "clear"	Cirrus	Nominal
74550	2	Lucinda	Water mode, water type "clear"	Cirrus	Nominal
76465	2	Lake Elsinore	Water mode, water type "clear"	Cirrus	Nominal
80440	2	Ystad	Water mode, water type "clear"	Cirrus	Nominal

Table 7-26 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

- **Masking**

First, the water mask is checked. The water body and the clouds, as well as shadows over land, are correctly masked (see Figure 7-27 and Figure 7-28). Despite, one can see that cloud – shadows are pretty hard to mask explicitly and thus often masked as water instead, since the spectral signals are too alike.

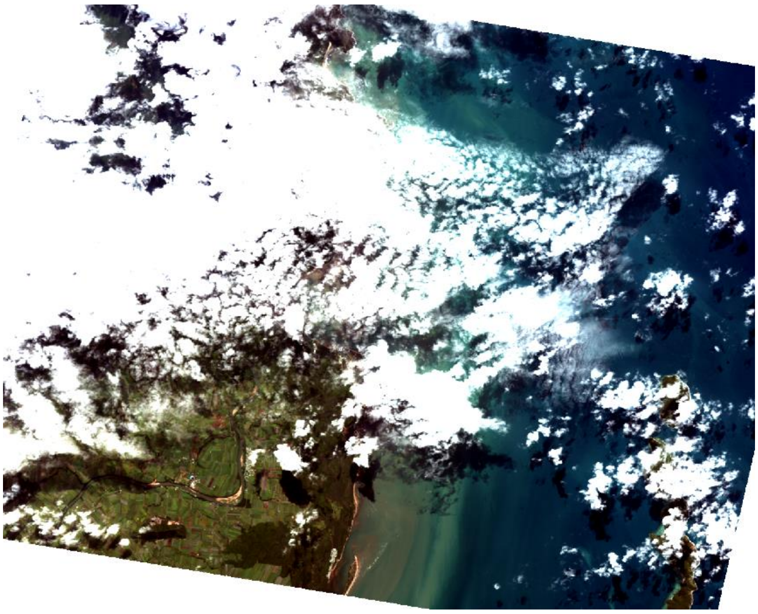


Figure 7-27 Scene-ID 74550; RGB-Quicklook with Bands 611.02nm – 550.69nm – 463.73nm

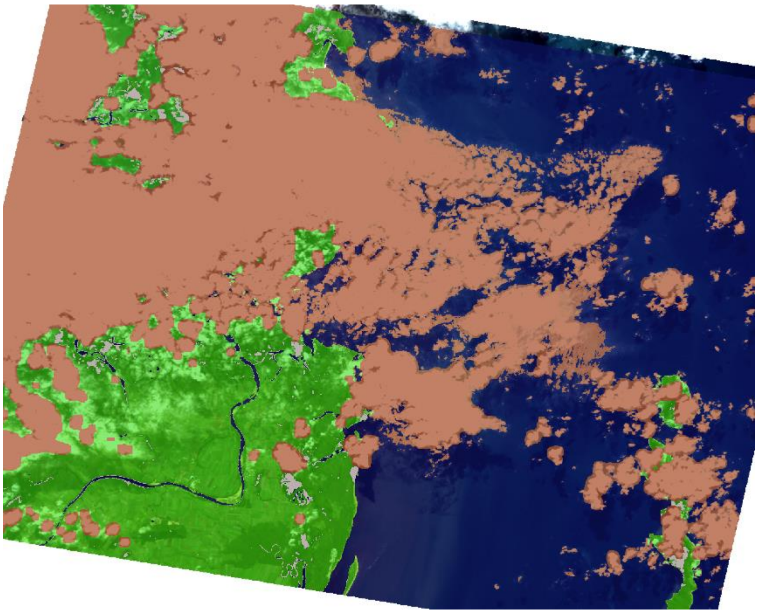


Figure 7-28 Scene-ID 74550; Geomask with Land in green, shadow in red, clouds in brown, water in blue

- **Adjacency Correction**

Next, we check for the adjacency correction using the two sites 'AC1' and 'AC2' showed in Figure 7-29.

Figure 7-29 Scene-ID 73100; RGB-Quicklook with Bands 611.02nm – 550.69nm – 463.73nm

The coordinates of the sample locations are as follows:

AC 1: LAT 47.66892775 | LON 9.17196235

AC 2: LAT 47.65719853 | LON 9.24859045

The location 'AC 1' is located right within the Rhine channel in Constance. Therefore we expect the amplitude of the applied correction on the signal to be much higher than it should be the case for location AC 2, located at some deeper part of Lake Constance, far apart from any highly reflective terrestrial features.

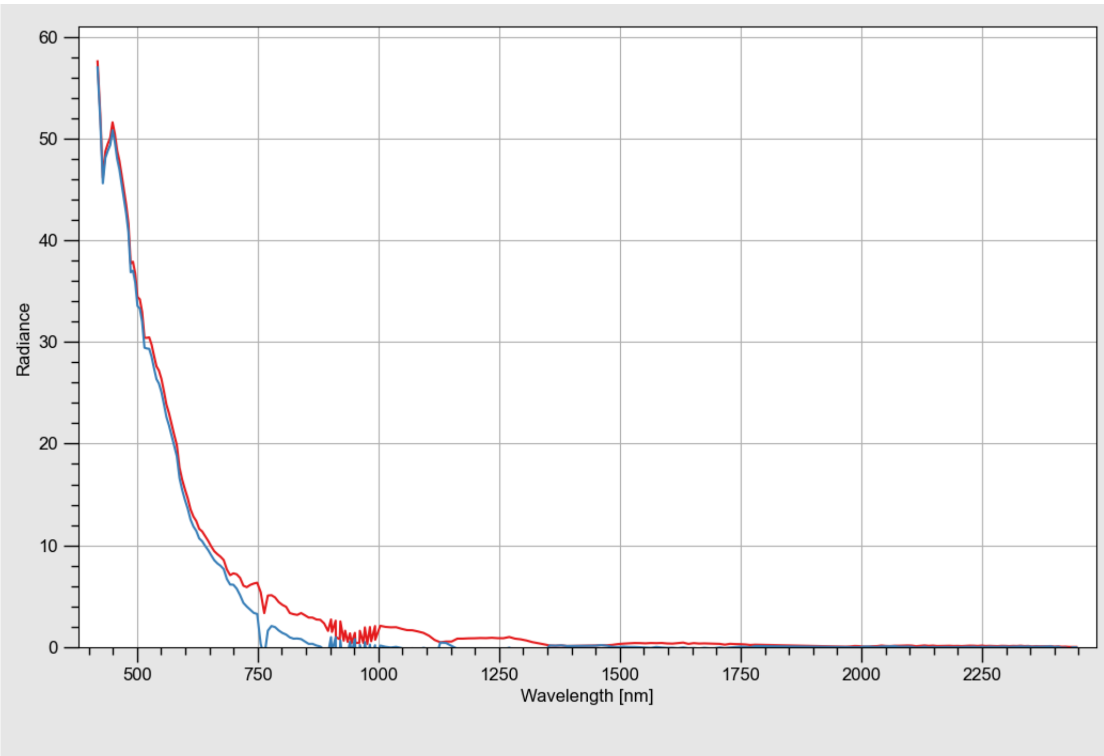


Figure 7-30 Scene-ID 73100; Signal sampled at location 'AC 1'; red: measured signal, blue: corrected signal

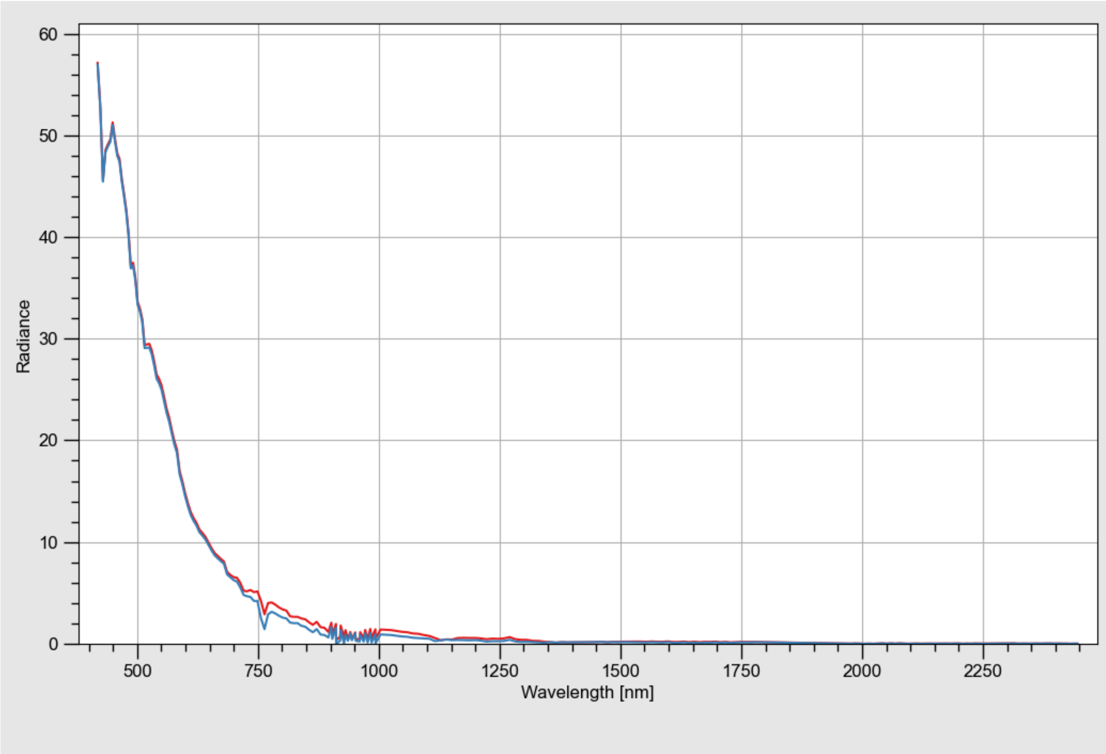


Figure 7-31 Scene-ID 73100; Signal sampled at location ‘AC 2’; red: measured signal, blue: corrected signal

In Figure 7-30 and Figure 7-31, respectively, the influence of this correction on the spectrum is depicted. As expected, the amplitude of the applied correction is high for AC 1. Since this sampling location is surrounded by high reflective terrestrial features, this example pretty clearly shows the intention of applying adjacency correction and its importance for locations near shore. If not applied here, the absolute signal would be far too high, and any analysis would suffer from this. To the contrary, when sampling at location ‘AC 2’ (Figure 7-31) we see, that the amplitude of correction is much reduced and in parts of the spectrum not even noticeable anymore.

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

- **Quality Mask**

Figure 7-32 and Figure 7-33 provide you with the RGB – Quicklook of the scene, used to check the quality masking, as well as with the corresponding quality mask. We can see here that the apparent sun-glint is masked as expected. More of interest are the pixels found to be of total quality of 0, only because of the respective atmospheric slope. For those pixels, the AOT was found to be very low, resulting in a very high slope value.

Figure 7-32 Scene-ID 76465; RGB-Quicklook with Bands 611.02nm – 550.69nm – 463.73nm

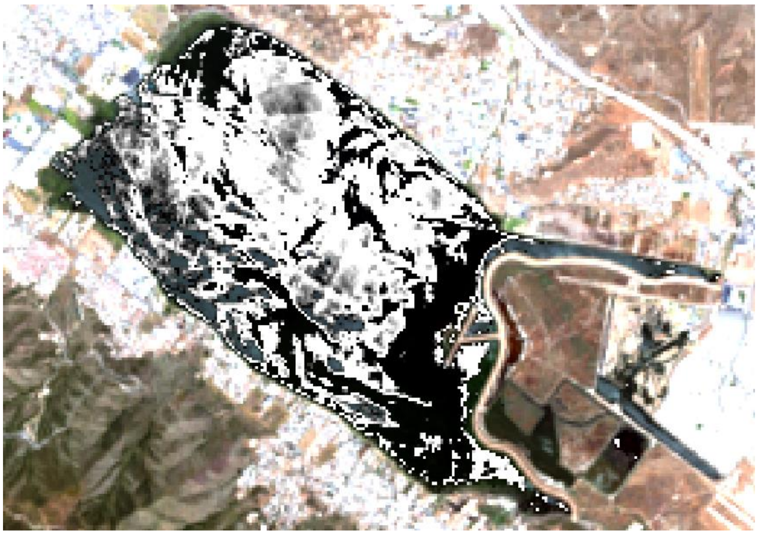


Figure 7-33 Scene-ID 76465; Quality mask in greyscale where white corresponds to 1

- **Reflectance Product**

To get a better impression of the product normalized water leaving reflectance as the final one, Figure 7-34 shows the reflectance using the RGB channels 611.02nm, 550.69nm and 463.73nm.

Figure 7-34 Normalized Water Leaving Reflectance of scene-ID 73100; Wavelengths for RGB: 611.02nm – 550.69nm – 463.73nm

For the two labeled locations in Figure 7-34, the sampling coordinates are as follows:

nWLR 1: LAT 47.67083360 | LON 9.10074516

nWLR 2: LAT 47.68178419 | LON 9.10123982

The following two plots, Figure 7-35 and Figure 7-36, depict the normalized water leaving reflectance (nWLR), sampled at the locations nWLR 1 and nWLR 2. nWLR 2 is located in an area of shallow water, holding a high concentration of organic matter. In comparison, at nWLR 1 the water is deeper and there is less organic material to be expected. When taking a look at the two corresponding spectra, we see those expectations being confirmed. Summing up, the normalized water leaving reflectance, as the final product, represents a highly appropriate dataset for further investigations, like retrieving details on the water content and much more. The applied correction algorithms, e.g. the correction for adjacency effects on pixels near shore, ensure to suppress disturbing parts of the at-sensor radiance.

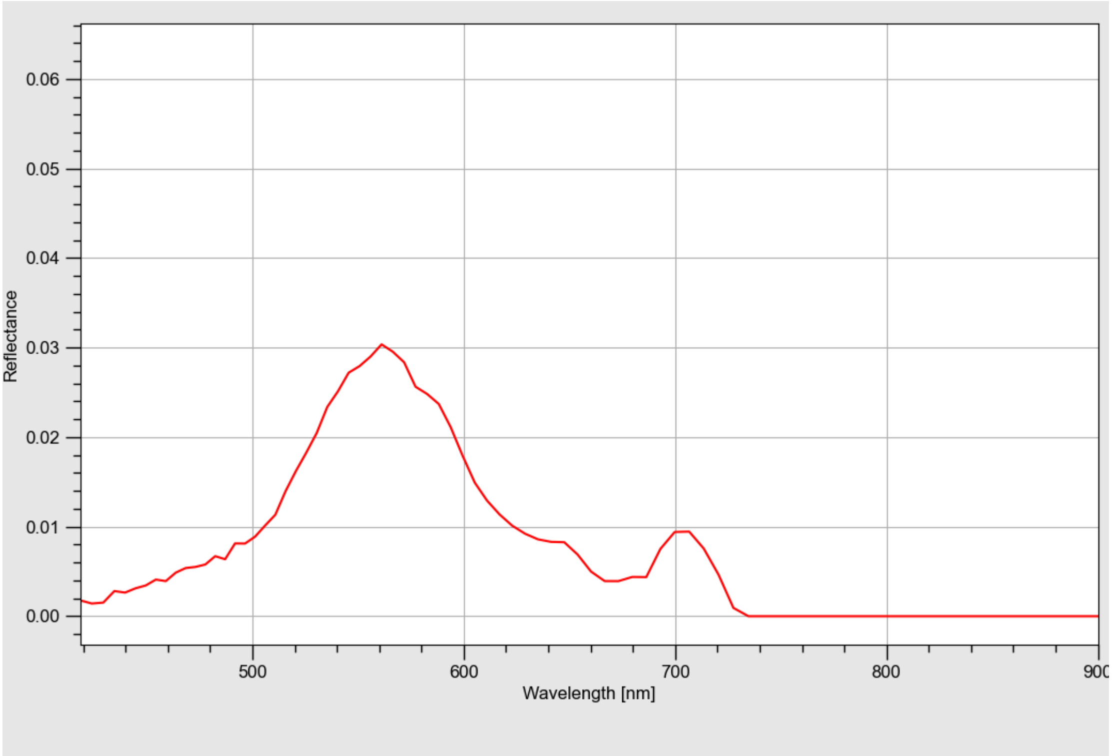


Figure 7-35 Scene-ID 73100; nWLR sampled at location nWLR 1

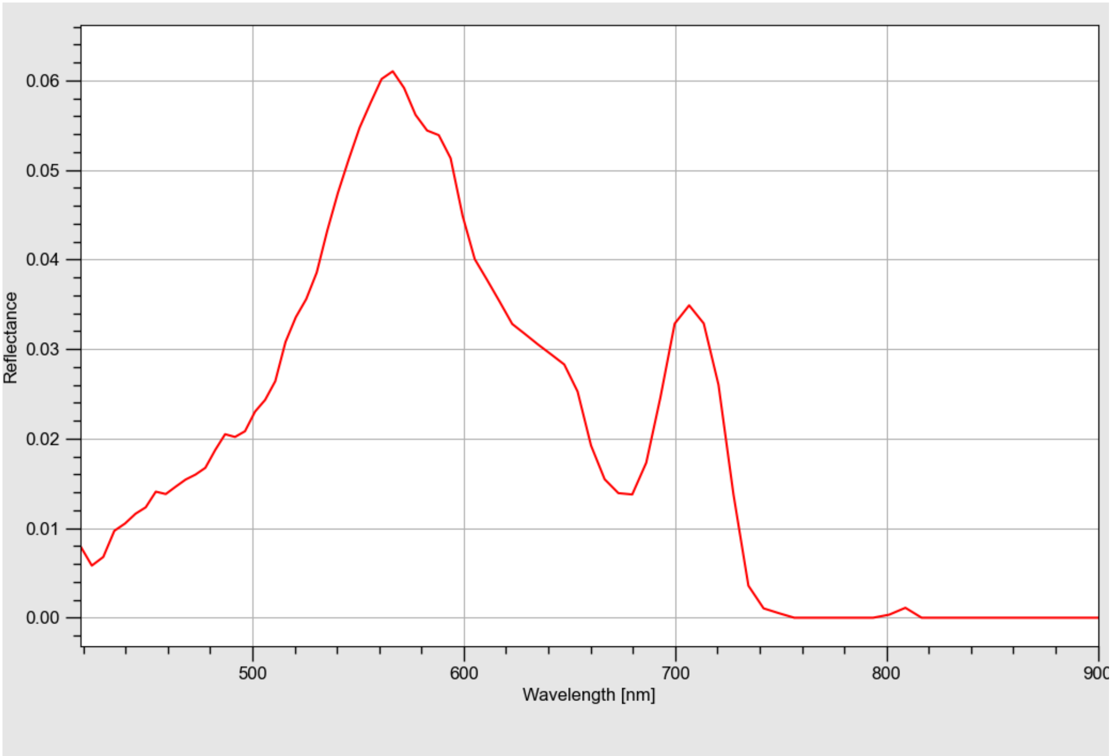


Figure 7-36 Scene-ID 73100; nWLR sampled at location nWLR 2

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

7.6.4.2.1 Analyzed scenes

Within the time interval between 2024-01-01 and 2024-03-31, an interactive in-depth analysis has been conducted for the following scenes:

datatakeID	tileID	date	location	L2A option	cirrus and haze removal	processor version	Overall Quality	Quality Atm
79739	20	16.06.2024	Spain	Land	Yes	V010402	Nominal	Nominal
79739	25	16.06.2024	Spain	Land	Yes	V010402	Nominal	Nominal
79739	30	16.06.2024	Spain	Land	Yes	V010401	Nominal	Nominal
80327	09	30.06.2024	Libya	Land	Yes	V010401	Nominal	Nominal
69359	14	17.04.2024	India	Combined	No	V010401	Nominal	Reduced

Table 7-27 Datatake ID of analyzed land products

For the selection of L2a data, care was taken to ensure a high degree of variety with respect to the geographical location of the data, external conditions (cloud cover) during the data take and processing parameters.

7.6.4.2.2 Data Checks

- **Checking of BOA_ref spectra and masks for 3 tiles of same datatake, including cross-check against interactive ATCOR processing for VNIR**

In the following, the tiles 20, 25 and 30 acquired over Spain (DT0000079739) were checked for the shape and magnitude of the BOA_ref spectra. Also the quality of the generated masks is evaluated. Furthermore, in order to check the influence of the aerosol retrieval, and also additional influences which might originate from geo-referencing, the standard L2A products of the same 3 datatakes were checked against the VNIR interactively processed with ATCOR for flat terrain (i.e., using the L1B VNIR cube as input).

For tile 20 (Figure 7-37), the visual image impression is fine. For the masking (Figure 7-38), only haze was detected over a few patches of the scene; visual inspection shows that this masking is plausible. The BOA_ref spectra (Figure 7-39) over vegetation, soil and shallow water all show the typical shape and magnitude, indicating the correct L2A correction. 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.

When comparing directly to ATCOR (Figure 7-40), the shape and magnitude of the VNIR part of the spectrum shows a very high level of agreement (Figure 7-41). Note that for this and the following similar comparisons, the corresponding areas were manually identified, and an average of 3x3 pixels was used to account for the influence of L1C resampling.

Similarly, for tile 25 (Figure 7-42), the visual image impression and the spectra for typical surfaces are plausible and as expected (Figure 7-44). Note that also for deep and shallow water included in tile 25, the spectra look as expected even though "land" processing mode was used. For the masking (Figure 7-43), the haze mask is highly plausible, while for the cloud mask also saturated pixels were masked as clouds; this behavior is well known and is by no means critical. As shown in Figure 7-45, the comparison with

ATCOR shows again a very high level of agreement, further demonstrating an accurate atmospheric correction within the L2A.

The same findings also apply to tile 30 (Figure 7-46), where the haze mask is plausible (Figure 7-47), the BOA_ref spectra are as expected (Figure 7-48), and the comparison with ATCOR (Figure 7-49) show a high level of agreement.

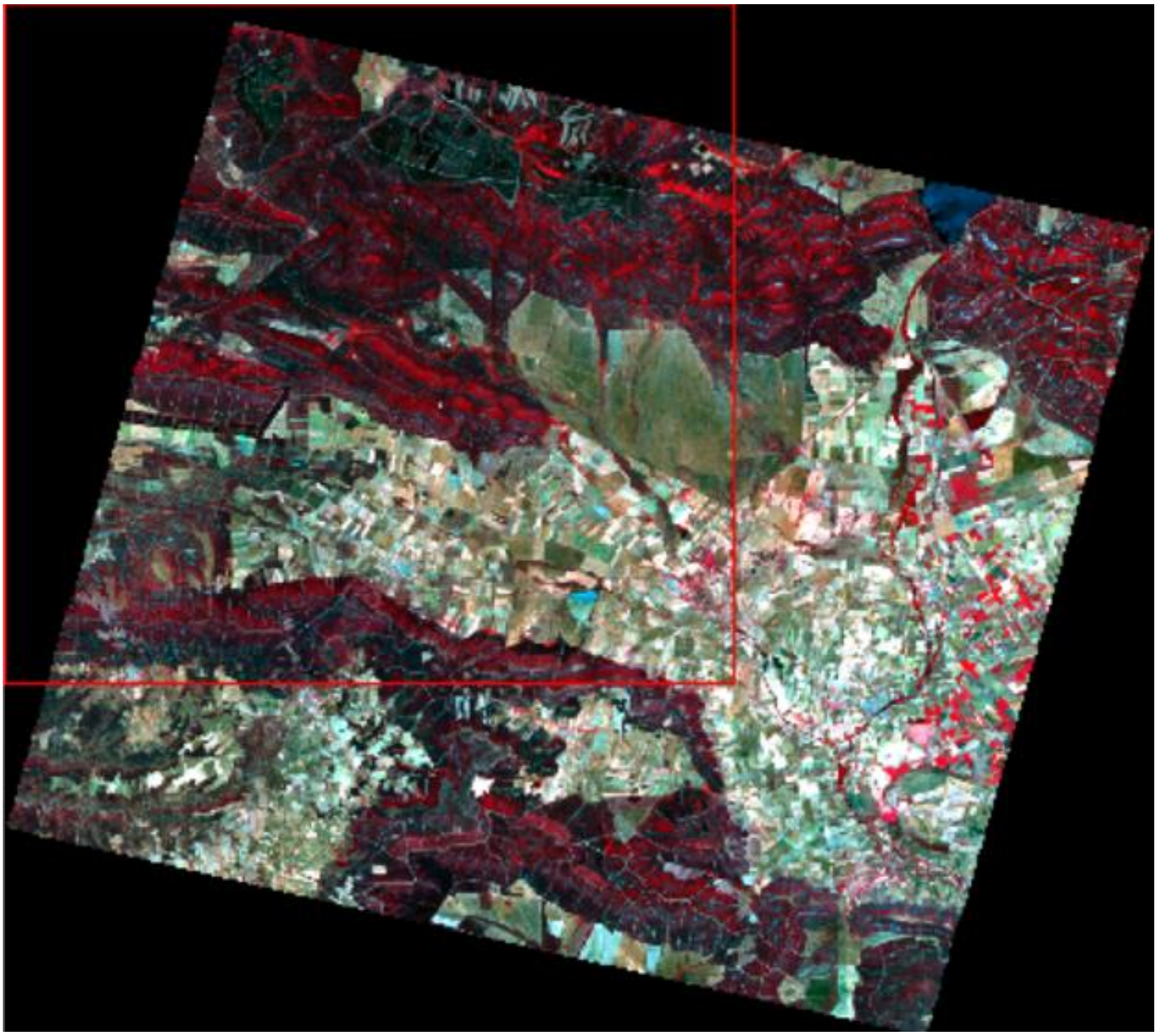


Figure 7-37 EnMAP L2A CIR composite (bands 75-45-28) of scene DT79739 Tile 20

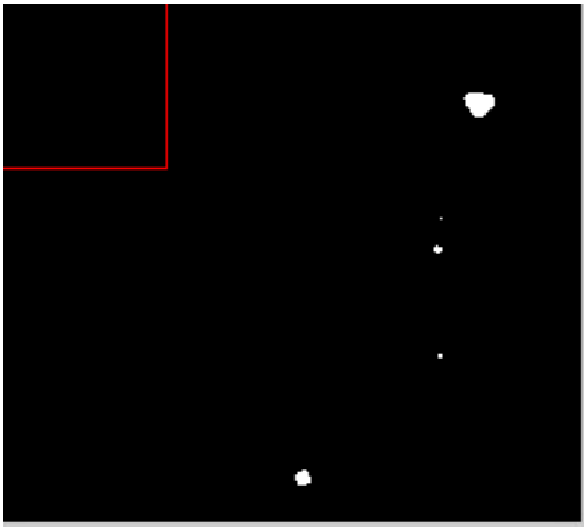


Figure 7-38 Haze mask for scene DT79739 tile 20; all other masks are -correctly- empty.

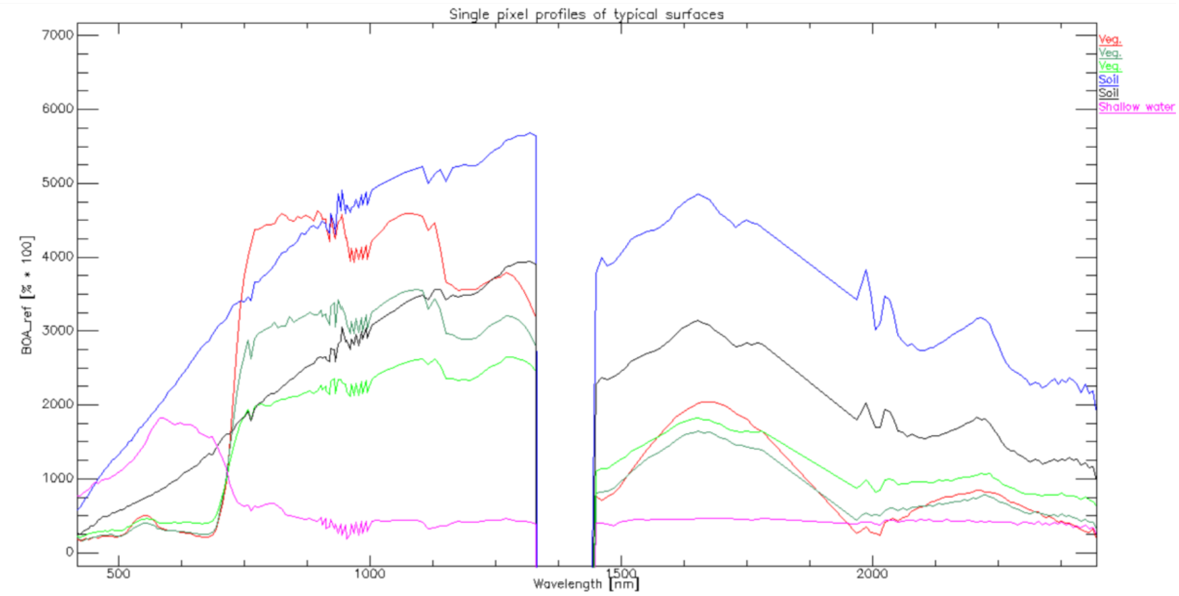


Figure 7-39 Typical image spectra (single pixel) of scene DT79739 Tile 20

Figure 7-40 Interactive ATCOR processed BOA_ref of scene DT79739 Tile 20 (CIR, bands 75-45-28); note the image is still in sensor geometry.

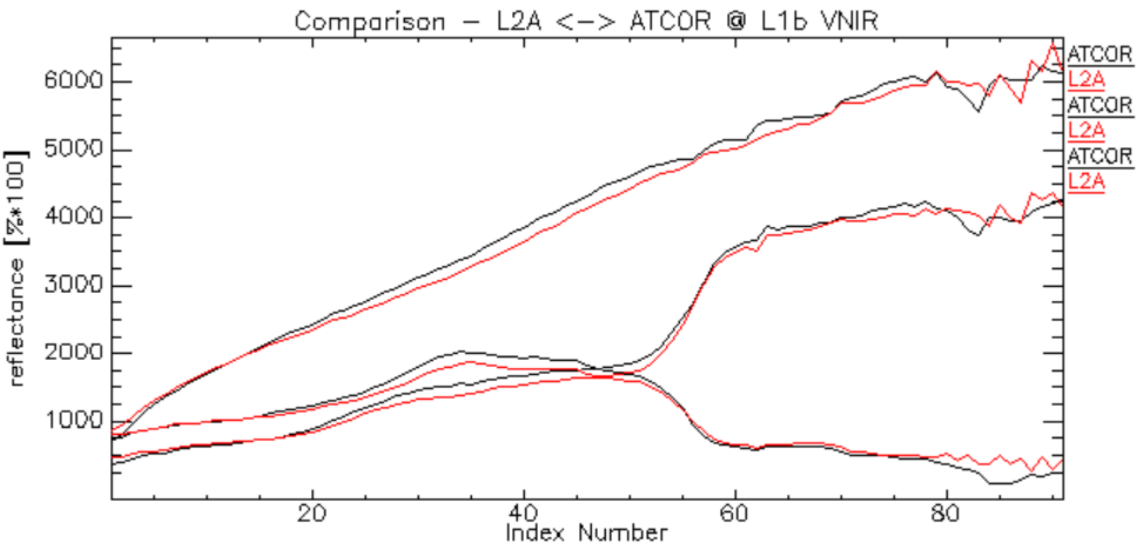


Figure 7-41 Comparison of L2A and interactive ATCOR (using L1b VNIR as input); average of 3x3 pix.; DT79739 Tile 20.

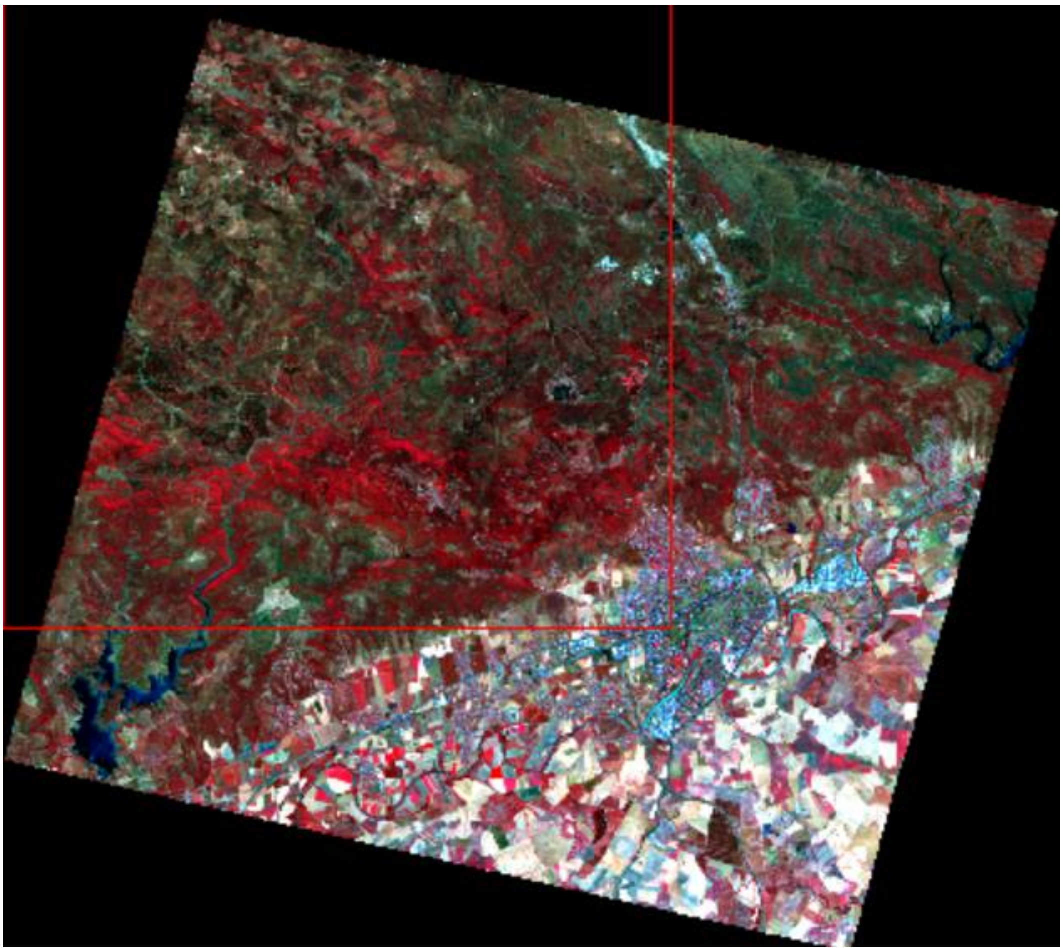


Figure 7-42 EnMAP L2A CIR composite (bands 75-45-28) of scene DT79739 Tile 25

Figure 7-43 Cloud (left) and haze (right) masks for scene DT79739 tile 25; all other masks are -correctly- empty.

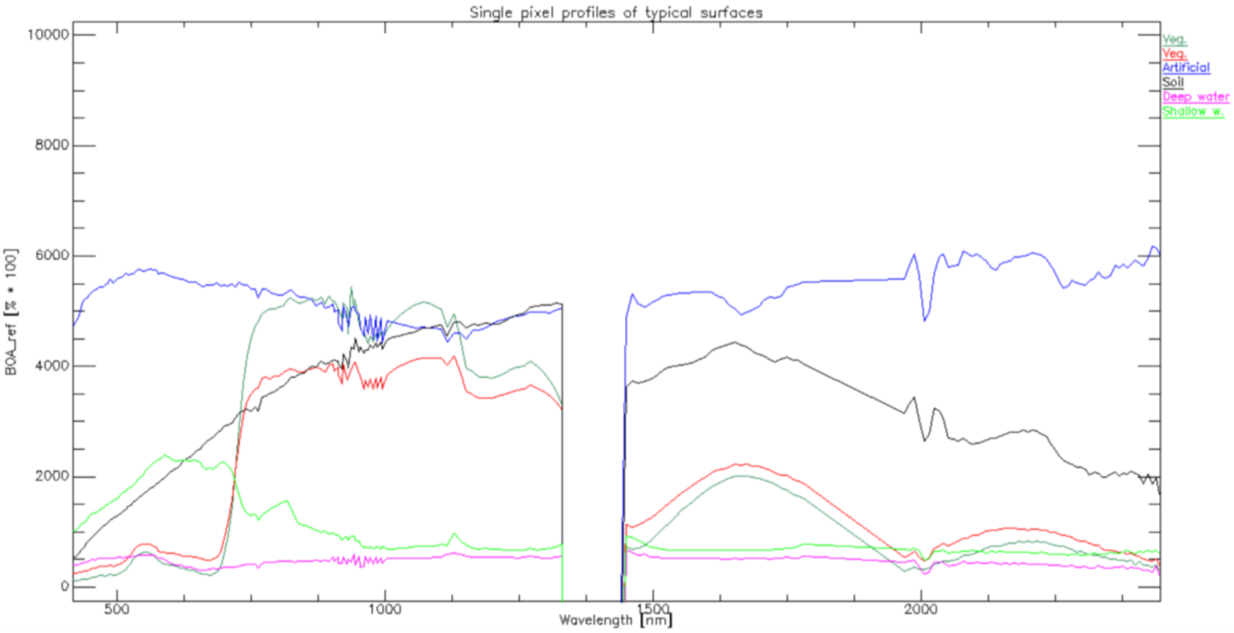


Figure 7-44 Typical image spectra (single pixel) of scene DT79739 Tile 25

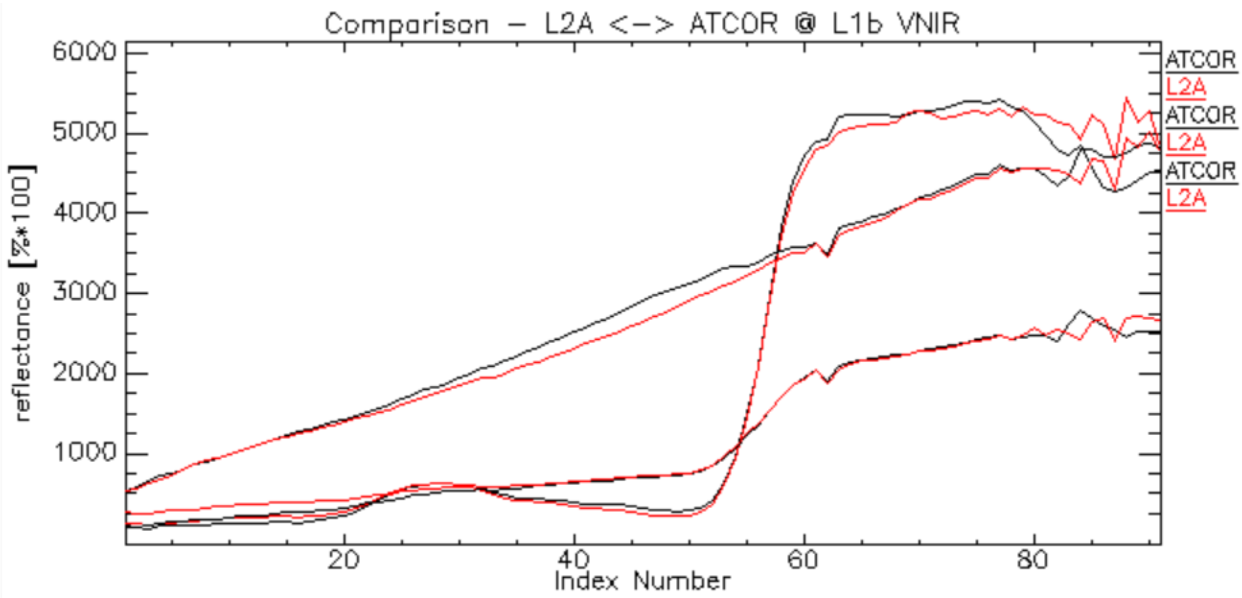


Figure 7-45 Comparison of L2A and interactive ATCOR (using L1b VNIR as input); average of 3x3 pix.; DT79739 Tile 25.

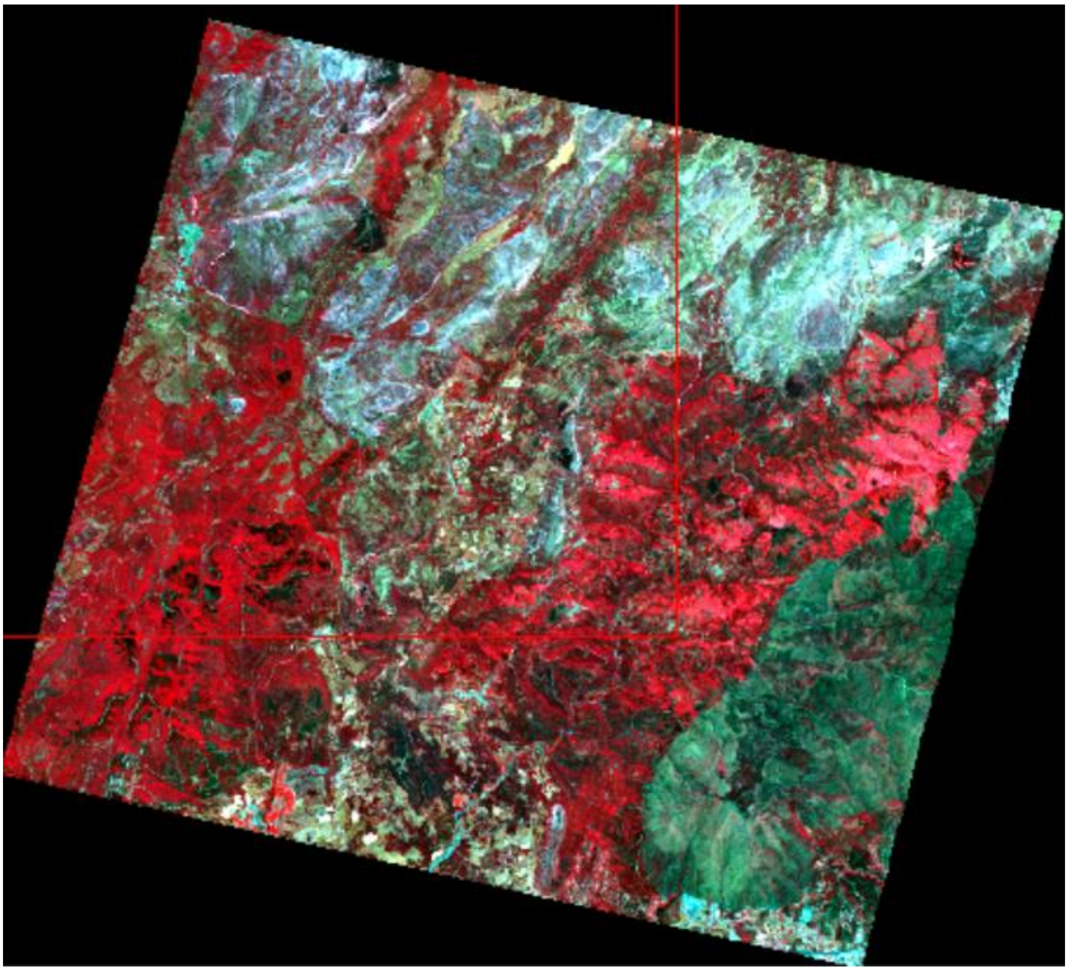


Figure 7-46 EnMAP L2A CIR composite (bands 75-45-28) of scene DT79739 Tile 30

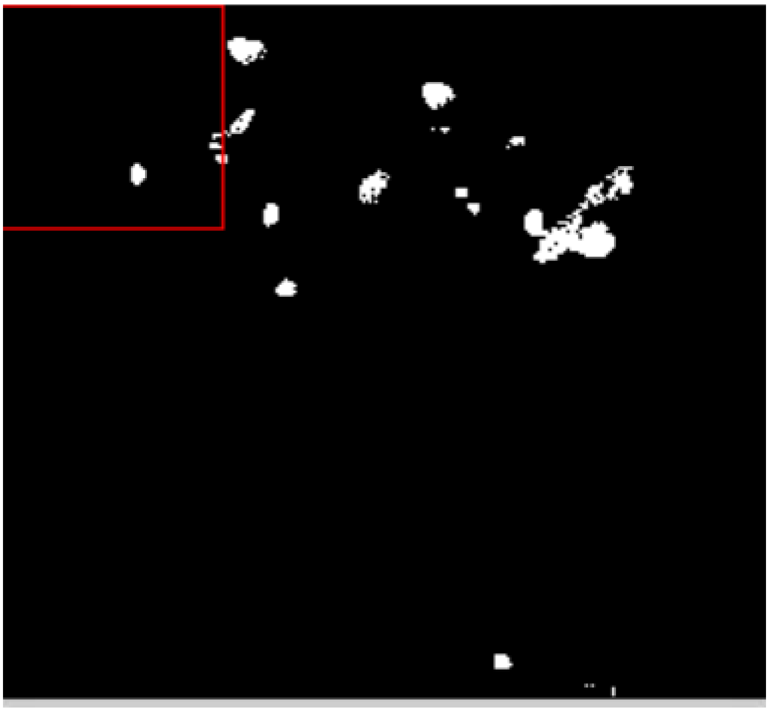


Figure 7-47 Haze mask for scene DT79739 tile 30; all other masks are -correctly- empty.

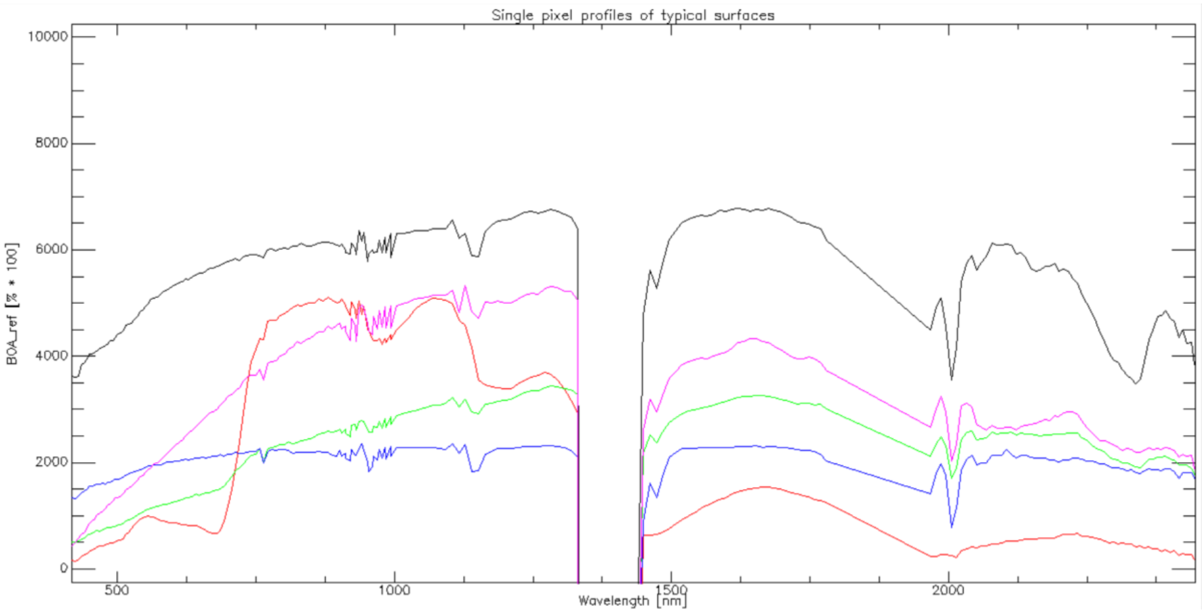


Figure 7-48 Typical image spectra (single pixel) of scene DT79739 Tile 30

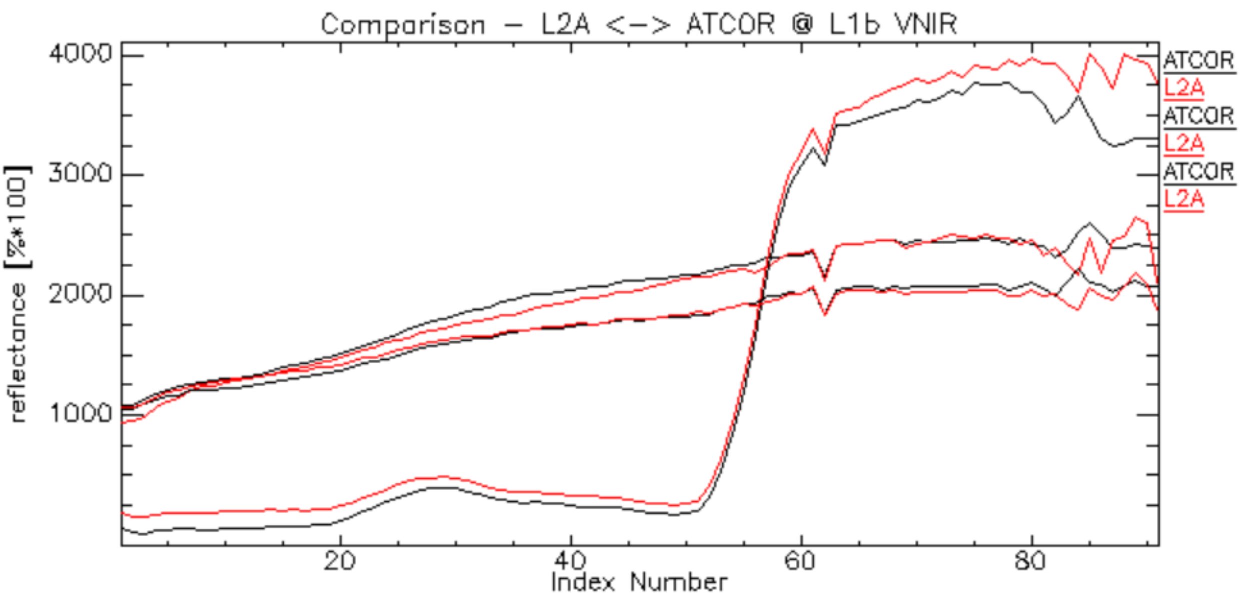


Figure 7-49 Comparison of L2A and interactive ATCOR (using L1b VNIR as input); average of 3x3 pix.; DT79739 Tile 30.

- **Checking of BOA_ref spectra and masks for a homogeneous desert site without DDVs**

The datake DT 80327 tile 9 over the Libya4 PICS site (Figure 7-50) was used to check the BOA_ref spectra for a case where no DDVs are available and thus the AOT backup algorithm is used. As expected for a PICS site, the BOA_ref spectra shown in Figure 7-51 all have a high reflectance of >60% reflectance in the NIR and SWIR; only few pixels show a lower reflectance (green curve in Figure 7-51), but the overall shape is highly similar. As expected, the spectral shape is very smooth except for the VNIR-SWIR overlapping bands. Also the generated masks are all correctly empty (not shown). To conclude, also that no DDV pixel are available, the fall back algorithm provides smooth and plausible spectra.

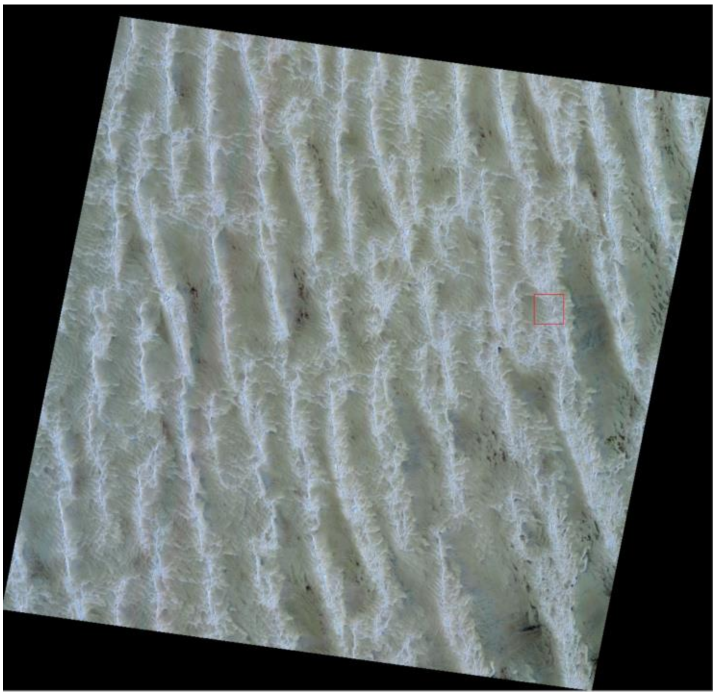


Figure 7-50 EnMAP L2A CIR composite (bands 75-45-28) of scene DT80327 Tile 9

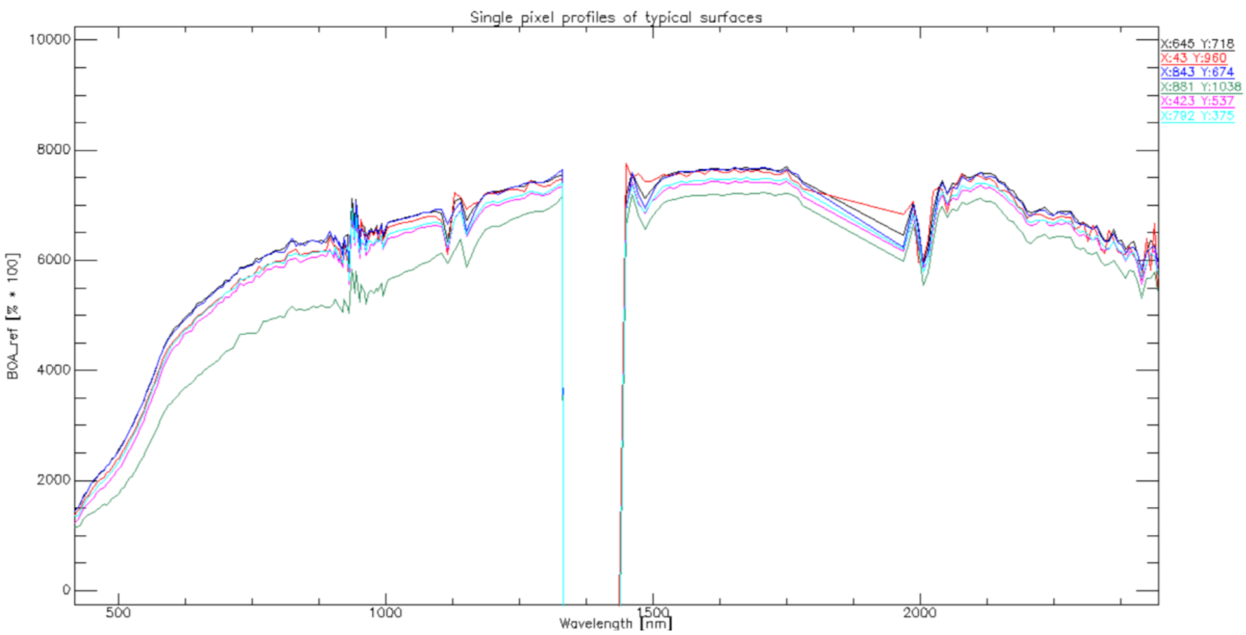


Figure 7-51 Typical image spectra (single pixel) of scene DT80327 Tile 9

- **Checking of BOA_ref spectra and masks for a scene with reduced atm. quality**

For the checking a scene with challenging atmospheric conditions, the DT 69359 tile 14 over India was chosen (Figure 7-52). As can be seen in the derived masks (Figure 7-53), the few clouds were correctly masked, and also the haze in the vicinity. The eastern parts of the scene at lower elevation are also affected by cirrus, which is included in the masks. For the resulting BOA_ref spectra (Figure 7-54), the vegetated areas as well as areas covered by soil and dry vegetation show the typical reflectance curves, both in shape and magnitude; the same applies to shallow and deep water spectra. For the spectra of clouds, some pixels show over 100% reflectance for bands below 600 nm, but this is expected for such a high radiance level outside the nominal range. For the given scene, also the overlap between VNIR and SWIR is visible, but the overall reflectance curve outside the overlap is smooth.

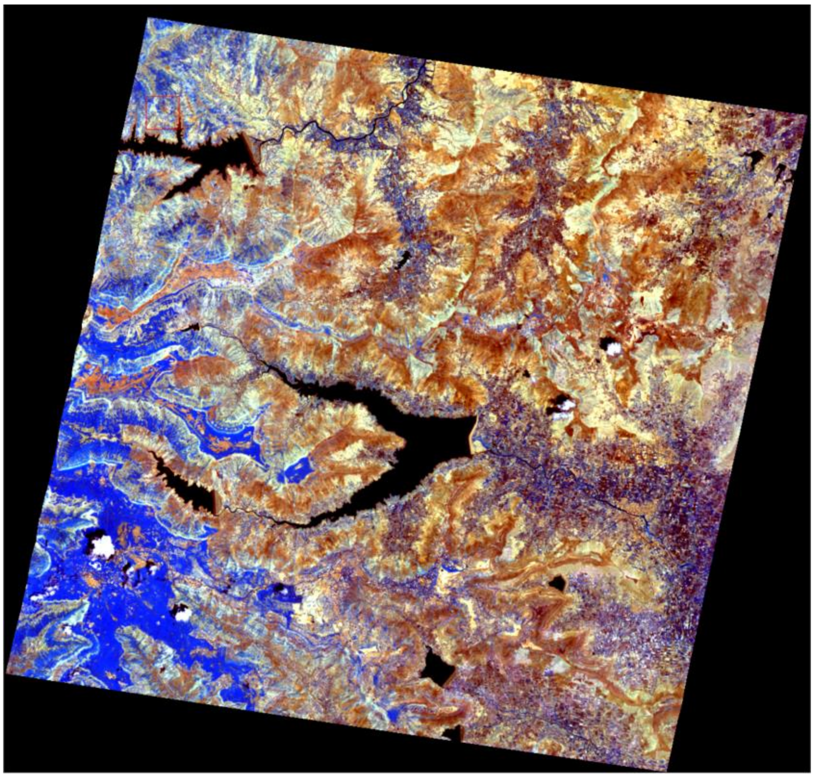


Figure 7-52 EnMAP L2A SWIR composite (bands 169-151-115) of scene DT69359 Tile 14

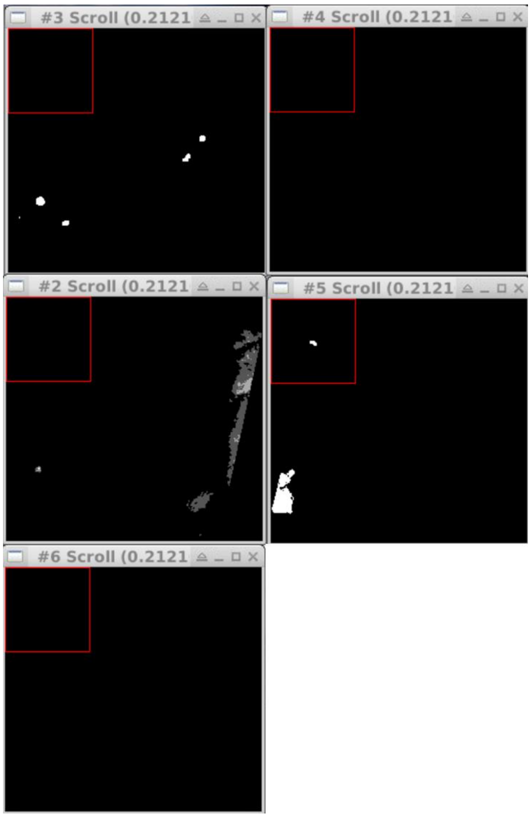


Figure 7-53 Masks generated for scene DT69359 Tile 14 . Top row: Cloud & Cloud shadow. Middle row: Cirrus & Haze. Bottom row: Snow.

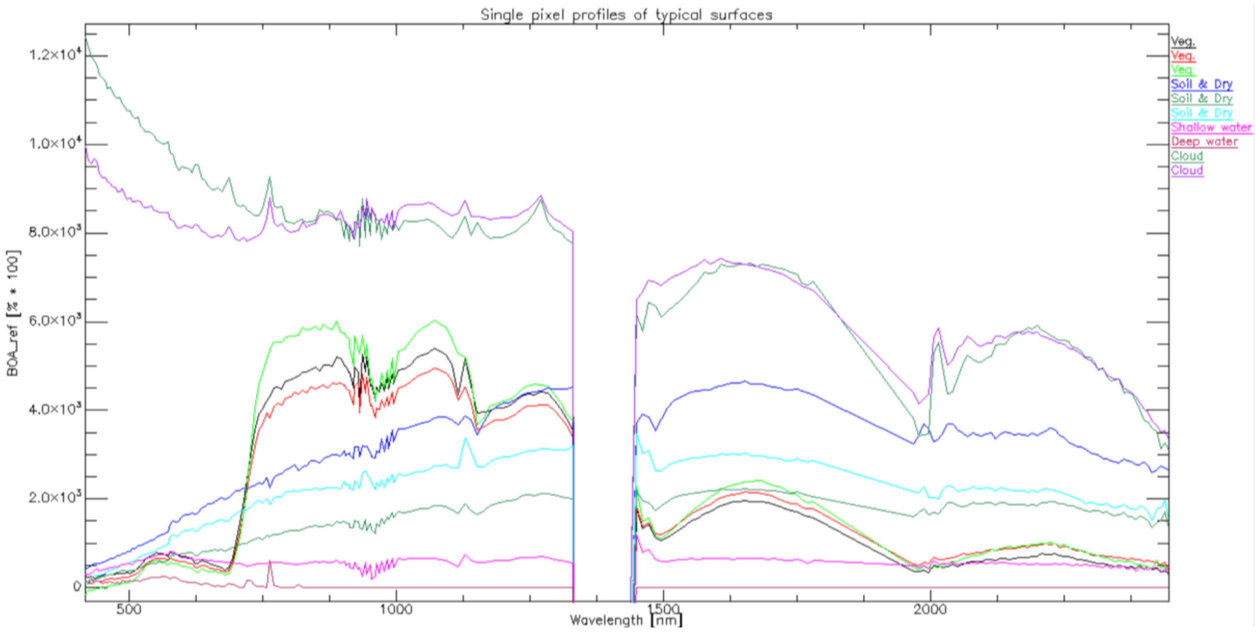


Figure 7-54 Typical image spectra (single pixel) of scene DT69359 Tile 14

8 External Product Validation

No special events or anomalies occurred during the reporting period. EnMAP products from the latest processor and archiving versions were validated and monitored regarding their standard quality parameters.

8.1 Level 1B

Level 1B products were validated in the reporting period regarding:

- TOA Radiance
- Spatially coherent radiometric miscalibration (striping artifacts; along- and across-track)
- Signal-to-Noise Ratio (SNR)
- Cross-matchups with EnMAP, EMIT, and PRISMA

For the TOA Radiance validation scenario, two additional matchups were integrated. No significant product quality changes were indicated, and the radiometric mismatch is with < 5% RMSE still inside the mission requirements.

The SNR assessment integrated three additional scenes and confirmed the stability in this regard and the fulfillment of the mission requirements (VNIR > 343:1 @495 nm SSD 4.7 nm; SWIR > 137:1 @2200 nm & SSD 8.4 nm).

The cross-validation between PRISMA, EMIT, and EnMAP was extended with two more matching scenes. However, the statistics do not pinpoint the differences between the sensors and respective systematic radiometric misregistrations. Additional matchups in the future will consolidate the statistics in this regard. The TOA reflectance fit between the missions is still within <10% TOA reflectance.

8.2 Level 1C

The geometric quality has been accessed based on Level 1C products:

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

The RMSE for co-registration between VNIR and SWIR wavelength domains is still around 3.5 m in both X and Y directions and is therefore stable for archived versions >= 01.04.00. No significant changes have happened since the last MQR, and the mission requirements of < 30 % of a pixel are still fulfilled.

The same is true for the absolute spatial accuracy. The statistics are stable, and the mission requirements have been fulfilled.

8.3 Level 2A

During the reporting period, several in-situ matchups were added to the L2A land and water quality assessment.

Land

For the land in-situ matchups, this has not changed the precision, accuracy, and RMSE statistic. For shorter wavelengths (< 500 nm) and greater wavelengths (> 2250) nm, the RMSE is still > 5%. The main driver for the shorter wavelength is the dominance of sites without DDV and the associated fallback to a standard atmospheric AOT value in the EnMAP atmospheric correction. For the longer wavelength domain, very low reflectance levels are the main driver of the RMSE. By filtering the matchups according to scenes for which an explicit AOT retrieval was performed, all RMSE values are below 3% and, therefore, well inside the mission requirements.

Water

Five valid additional matchups were available for the water part for the reporting period. Several in-situ data for successful matchups were not yet available, but they will be included in the following report. All available valid matchups (20) were processed according to the station's water type (clear, turbid, and high-turbid waters) with the new processor version 01.04.02. The validation with version v01.04.02, which now distinguishes between water types and uses a higher spectral sampling, indicates a significant improvement regarding spectral noise compared to <01.04.00, particularly below 500 nm. The previously inherent characteristic spike between 700nm and 800nm was also reduced for several matchups. However, for individual matchups, the spike is still remarkable. This will be further investigated in the future based on additional matchups.

8.4 Summary of External Product Monitoring

All validation and quality monitoring efforts during the reporting period indicated that the product quality is stable and all respective mission requirements are fulfilled. For the L2A water product, the processor version 01.04.02 significantly improved the data quality.

9 Others

EnMAP Mission Operations and Status Publications:

EnMAP Mission Operations and Status Presentations:

- Presented at EARSeL 2024 Workshop (16–18 Apr 2024, Valencia):
  - “EnMAP: The German Hyperspectral Mission” (L. La Porta et al.)
  - “EnMAP Mission After 2 Years in Orbit: Advances from the Scientific Exploitation Program” (S. Chabrillat et al.)
  - “EnMAP: A breakthrough for Hyperspectral Earth Observation. Seen from the manufacturer of the satellite, 2 years after Launch” (R. Feckl et al.)
  - “Two years of EnMAP Ground Segment Operations” (E. Carmona et al.)
  - “Status of EnMAP processor and calibration activities” (M. Pato et al.)
  - “A Brief History of the Inflight Spectral and Radiometric Performance of EnMAP” (D. Marshall Ingram et al.)
  - “EnMAP data product validation: lessons learned from two years in orbit” (M. Brell et al.)
  - “Hyperspectral EnMAP Data Processing for Aquatic Science and Applications” (N. Pinnel et al.)
  - “Evaluating the EnMAP L2A normalized water leaving reflectance product over two years of mission” (M. Soppa et al)
- EARSeL Post-workshop tutorial:
  - “EnMAP IPP User Portal” (N. Pinnel)