Technical Note on Quality Assessment for NEMO-HD Still Imagery

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TABLE OF CONTENTS

AMENDMENT RECORD SHEET

The Amendment Record Sheet below records the history and issue status of this document.

ISSUE	DATE	REASON
0.1	25 01 2022	First draft for ESA review
1.0	07 04 2022	First issue

1. INTRODUCTION

The primary objective of the Next-generation Earth Monitoring and Observation – High Definition (**NEMO–HD**) microsatellite is to explore a new Earth Observation (**EO**) concept, which combines high resolution optical video and still imagery for interactive real-time and low latency remote sensing services.

The aforementioned data quality assessments are performed in accordance with the assessment guidelines, detailed in [RD-1, RD-2], that constitute the European Space Agency (**ESA**) Earthnet Data Assessment Pilot (**EDAP**) Project's *EO Mission Data Quality Assessment Framework*. An important representation of the latter framework, constructed by the National Physical Laboratory (**NPL**, U.K), is what is known as the *maturity matrix*. It is a diagrammatic summary of the following:

- ***Documentation Review****: the EDAP optical team reviews materials provided by the mission provider (e.g. ancillary / auxiliary data and documentation), some of which may not be publicly available, or even the scientific community (e.g. published papers). The results are detailed in Section 3 (covering the first four columns of the maturity matrix, see Table 3-1).*

- ***Data Quality Assessments:*** *the EDAP optical team performs data quality assessments (i.e. validation assessments), independently of those performed by the mission provider. The results are detailed in Section 4 (covering the last column of the maturity matrix, see Table 3-1).*

The above data quality assessments are performed by the project's optical team using the appropriate in-house and open-source ad-hoc scripts / tools.

It is important to note the purpose of the *EDAP EO Mission Data Quality Assessment Framework* is to ensure that the delivered commercial mission data is fit for purpose and that all decisions regarding the inclusion of the commercial mission as an ESA third party mission can be made fairly and with confidence.

1.1 Reference Documents

The following is a list of reference documents with a direct bearing on the content of this proposal. Where referenced in the text, these are identified as [RD-n], where 'n' is the number in the list below:

RD-1. EDAP Best Practice Guidelines, EDAP.REP.001, v1.2, September 2019.

RD-2. Earth Observation Mission Quality Assessment Framework – Optical Guidelines, EDAP.REP.002, v2.0, December 2020.

RD-3. SPACE-SI Product User Manual for NEMO-HD, v1.0, 11 March 2022.

RD-4. SPACE-SI NEMO-HD Product Details. (no version or date)

RD-5. SPACE-SI NEMO-HD Product Metadata Specification. (no version or date)

RD-6. SPACE-SI Algorithm Theoretical Basis Document for Multispectral Images, v0.1, 31 August 2021.

RD-7. SPACE-SI Algorithm Theoretical Basis Document for Orthoimages, no version information.

RD-8. Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., et al. 2016 The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3, 160018. (doi:10.1038/sdata.2016.18)

RD-9. Preflight Sky Image Analysis, February 2016.

RD-10. Preflight Payload Test Report, v002, 05 April 2013.

RD-11. SPOT Image Quality Performances, CNES C443-NT-0-296-CN, https://www.intelligence-airbusds.com/files/pmedia/public/r438_9_spot_quality_performances_2013.pdf

RD-12. M. Cournet, A. Giros, L. Dumas, J.M. Delvit., D. Greslou, F. Languille, G. Blanchet, S. May, and J. Michel (2016). 2D Sub-Pixel Disparity Measurement Using QPEC / Medicis, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLI-B1, 291-298, doi: 10.5194/isprs-archives-XLI-B1-291-2016.

RD-13. John Pike, National Image Interpretability Scale. 1998, https://fas.org/irp/imint/niirs.htm Accessed online: 22 October 2021

RD-14. Françoise Viallefont-Robinet, Dennis Helder, Renaud Fraisse, Amy Newbury, Frans van den Bergh, Donghan Lee, Sébastien Saunier. Comparison of MTF measurements using edge method: towards reference data set. Optics Express, Optical Society of America, 2018, 26 (26), pp.33625-33648. ⟨hal-02055611⟩

1.2 Glossary

The following acronyms and abbreviations have been used in this Report.

ATBD	Algorithm Theoretical Basis Documents
CEOS	Committee for Earth Observing Satellites
EDAP	Earthnet Data Assessment Pilot
EO	Earth Observation
ESA	European Space Agency
ESF	edge spread function
GSD	Ground Sampling Distance
HR	High Resolution
MS	Multispectral
MTF	Modulation Transfer Function
NEMO–HD	Next-generation Earth Monitoring and Observation – High Definition

NIIRS	National Imagery Interpretability Rating Scale
NPL	National Physical Laboratory
PAN	panchromatic
PHR	Pleaides High-Resolution
POI	points of interest
PSF	Point Spread Function
SNR	Signal-to-Noise Ratio
Space-SI	Slovenian Centre of Excellence for Space Sciences and Technologies
VHR	Very High Resolution

2. EXECUTIVE SUMMARY

The NEMO-HD microsatellite, developed and operated by the Slovenian Centre of Excellence for Space Sciences and Technologies (**SPACE-SI**) in collaboration with the University of Toronto's Institute for Aerospace Studies, provides the user community with High Resolution (**HR**) multispectral (**MS**) and panchromatic (**PAN**) imagery of the Earth's surface.

The results of the preliminary data quality assessments performed on the sample of **orthorectified bundle** products, procured from the mission provider (operator and data provider) **Space-SI** between July and September 2021, are summarised in Table 2-1.

Table 2-1: NEMO-HD: Assessment Area Results

Assessment Area	Results
(collected) Ground Sampling Distance (**GSD**) / Pixel Size @ Nadir: Panchromatic 2.8 m / 2.8 m, Multispectral 5.6 m / 5.6 m.	
Geometric Calibration Quality	**1. Absolute Geolocation Accuracy** The results of this assessment indicate the absolute (planimetric) geolocation error of the sensor's multispectral and panchromatic imagery is in the order of four to five pixels CE90. These results can be considered as good. No minimum performance requirement has been specified by the operator for this metric. **2. Temporal Geolocation Accuracy** The temporal geolocation accuracy could not be assessed due to the very small sample of suitable products procured. **3. Band Co-registration Accuracy** The results of this assessment indicate the co-registration of all multispectral and panchromatic bands is reasonably good / accurate but that it depends on image quality (e.g. the method used to co-register the bands relies on some form of image matching algorithm, which is only successful if there is good contrast levels in the imagery). No minimum performance requirement has been specified by the operator for this metric.
Radiometric Calibration Quality	The radiometric calibration quality assessments could not be performed as the data has not yet been radiometrically calibrated. This is most likely due to the maturity of the mission (the product metadata contains placeholders for the relevant parameters). **1. Absolute Radiometric Accuracy**

	This assessment had not been performed as the data is not radiometrically calibrated. No minimum performance requirement has been specified by the operator for this metric **2. Temporal Radiometric Accuracy** This assessment had not been performed as the data is not radiometrically calibrated. No minimum performance requirement has been specified by the operator for this metric.
Image Quality	**1. Modulation Transfer Function** The results of this assessment inficate the MTF@N_f is far lower than the MTF@N_f determined pre-launch. This is expected, as this was assessed here using imagery from higher-level processing, but it is recommended that it be reassessed and monitored by the operator post-launch. No minimum performance requirement has been specified by the operator for this metric. **2. Signal-to-Noise Ratio** This assessment has not been performed as the tool developed for this project currently expects only radiometrically calibrated (i.e. top-of-atmosphere radiance) data as input. No minimum performance requirement has been specified by the operator for this metric. **3. Image Interpretability** The results of this assessment indicate the multispectral and panchromatic imagery of this sensor is of a quality that allows points of interest, which correspond to its interpretability category, to be delineated. However, this can be improved with the reduction of blurring (and is especially evident when the imagery of the visible bands is compared to reference imagery from Pléiades' visible bands). No minimum performance requirement has been specified by the operator for this metric.
Visual Inspections	The results of the visual inspections indicate there are no anomalies or artefacts present in the multispectral and panchromatic imagery of the sample products procured.

3. EDAP QUALITY ASSESSMENT

3.1 EDAP Maturity Matrix

Table 3-1 Maturity Matrix for NEMO-HD Imagery

Product Information	Product Generation	Ancillary Information	Uncertainty Characterisation	Validation
Product Details	Sensor Calibration & Characterisation Pre-Flight 🔒	Product Flags	Uncertainty Characterisation Method	Reference Data Representativeness
Product Availability & Accessibility	Sensor Calibration & Characterisation Post-Launch	Ancillary Data	Uncertainty Sources Included 🔒	Reference Data Quality
Product Format 🔒	Additional Processing 🔒		Uncertainty Values Provided	Validation Method
User Documentation			Geolocation Uncertainty 🔒	Validation Results
Metrological Traceability Documentation				

Key
Not Assessed
Not Assessable
Basic
Intermediate
Good
Excellent

🔒 Information not public

3.1.1 Product Information

Product Details	
Grade: Intermediate *Justification: As there is some required and recommended information missing (usually included in product metadata, documentation, etc.), the status of this section of the maturity matrix has been graded as "Intermediate".*	
Product Name	*Basic Image / Orthoimage*
Sensor Name	*NEMO-HD*
Sensor Type	*(Pushbroom) Optical (Visible and Near-Infrared): Multispectral –> Blue: 420 – 520 nm, Green: 535 – 607 nm, Red: 634 – 686 nm and Near-Infrared: 750 – 960 nm. Panchromatic –> 400 – 900 nm*
Mission Type	*Single Satellite*
Mission Orbit	*Sun-synchronous (517 km Altitude, 10:30 AM Descending Node Local)*
Product Version Number	*v0.1*
Product ID	*NHDxxx_xxD_[MS,P]_ortho.tif – sensor & site, observation ID, multispectral or pan and then ortho at end of filename to indicate an Orthoimage*
Product Processing Level	*Level 3 (Orthoimage)*
Measured Quantity Name	*Digital Numbers (16-bit, scaled from 8-bit)*
Measured Quantity Units	*Unitless*
Stated Measurement Quality	*Radiometric Calibration Quality: Not Specified. Geometric Calibration Quality: Not Specified.*
Spatial Resolution	*High Resolution Multispectral: 5.6 m GSD @ nadir Panchromatic: 2.8 m GSD @ nadir Full Swath Width @ Nadir: 10 km Multispectral 9 km Panchromatic*
Spatial Coverage	*Global*
Temporal Resolution	*6 - 13 Days (Latitude Dependent)*
Temporal Coverage	*This microsatellite was launched into orbit 03 September 2020 and has an expected operational lifetime of 3 - 5 years.*
Point of Contact	*SPACE-SI Aškerčeva 12 SI-1000 Ljubljana Slovenija Tel: +386 40 866 945, Email: info@space.si*
Product locator (DOI/URL)	*The sensor products are made available upon request to SPACE-SI.*
Conditions for access and use	*Not provided.*

Limitations on public access	*No public access.*
Product Abstract	*Level 3 (Orthoimage): "Radiometric, sensor and geometric corrections applied to the data. The product accuracy depends on the quality of the ground control and DEMs used."[RD-3]* *"With NEMO-HD in orbit, SPACE-SI has achieved a very innovative and cost-effective remote sensing system that combines the agile microsatellite with the novel transportable ground station system and advanced data processing chain. The main applications of the data are aimed at monitoring smart cities, river basins and maritime as well as for enhanced EO applications for forests, agriculture, droughts, floods, and invasive plants." [RD-3]*

Availability & Accessibility	
Grade: Basic *Justification: The products and their content are compliant with some of the 'Findable, Accessible, Interoperable and Reusable Data Principles' for scientific data management and stewardship [RD-8].*	
Compliant with FAIR principles	*The products and their content are compliant, where applicable, with some of the 'Findable, Accessible, Interoperable and Reusable Data Principles' for scientific data management and stewardship [RD-8]. However, it is recommended the products be released with a clear and accessible data usage licence.*
Data Management Plan	*This is not shared by the mission provider.*
Availability Status	*The products are not currently available publicly but, according to [RD-3], the intention is to make georeferenced and pansharpened imagery available publicly via the Copernicus Open Access Hub web platform.*

Product Format	
Grade: Intermediate *Justification: The product format and content, in which standard file formats and naming conventions are generally used, is only partially described in [RD-5]; product metadata file format and content are not fully described, and product quality metadata is not available.* *It is recommended that existing documentation be updated in order to ensure the format and contents of all products are described fully, where applicable, for full understanding of the product. It is also recommended, for ease of use by the user, that filename format is consistent and descriptive (e.g. including the date of acquisition).* *The data is not considered as analysis ready data (e.g. Committee for Earth Observing Satellites (**CEOS**) Analysis Ready Data, https://ceos.org/ard/).*	
Product File Format	*The product contents, which adopt standard file formats, include the following:* *• Product Image (.TIF)*

	• *Product Image Metadata (.XML)* *The product format applies to the product procured for these assessments (i.e., Level 3) so deviations may exist for products of a different type.*
Metadata Conventions	*Not implemented as optional (e.g., Geographic Information – Metadata ISO).*
Analysis Ready Data?	*The sample products procured are not considered as analysis ready data.*

User Documentation
Grade: Basic
Justification: The current draft of the product user manual, provided upon request to the SPACE-SI, contains a good level of information only (e.g., payload description, operational context, product processing chain, product description, etc.). However, the draft is missing important information on spectral properties (e.g. normally the manual would include a table showing the bandwidths/central wavelength for each waveband) and instructions, once the data is radiometrically calibrated, that allows users to convert the data from digital numbers to top-of-atmosphere reflectances. *The current draft of the Algorithm Theoretical Basis Documents (**ATBD**) has also been provided, provided upon a non-disclosure agreement, and it also contains a good level of information.* *However, as the basic information on spectral properties is missing, this section of the maturity matrix has been graded as 'Basic'.*

Document	*Reference*	*QA4ECV Compliant*
Product Guide	*[RD-3]*	*No*
Algorithm Theoretical Basis Document for Basic Images	*[RD-6]*	*No*
Algorithm Theoretical Basis Document for Ortho Images	*[RD-7]*	*No*

Metrological Traceability Documentation	
Grade: Not assessable.	
Reference	*Document not made available.*

3.1.2 Product Generation

Sensor Calibration and Characterisation – Pre-Launch	
Grade: Basic *Justification: Pre-launch information has been provided, but the documentation supplied is not specifically related to the radiometric or geometric calibration. As there is no information on the latter as well as spectral calibration and characterisation activities, this section of the maturity matrix has been graded as 'Basic'.*	
Summary	*These documents provide high-level information on the pre-launch activities.*
Reference	*[RD-9] and [RD-10] not made available to users.*

Sensor Calibration and Characterisation – Post-Launch	
Grade: Not assessable	
Summary	*-*
Reference	*-*

Additional Processing	
Grade: Intermediate *Justification: An ATBD describes the processing steps carried out for orthorectification, including the approach with the procedure currently using 30 m spatial resolution SRTM DEM data. However, the document has no front page, contents table, version control etc. So, this section of the maturity matrix has been graded as 'Intermediate'.*	
Summary	*Orthorectification described in document.*
Reference	*[RD-7] Documentation*

3.1.3 Ancillary Information

Ancillary Data	
Grade: Basic *Justification: Some of the key ancillary data required to define measurement data has been provided, but other important ancillary data is missing (e.g. geometric and radiometric uncertainties), and so this section of the maturity matrix has been graded as 'Basic'.*	
Description	*The product-specific ancillary data (e.g., viewing and solar geometry angles, longitude, latitude, altitude), used to define measurements, can be found in product metadata. However, the documentation does not include information on / sources for radiometric information (e.g., in-band solar irradiance) and the uncertainties have not been quantified, where applicable, for ancillary data.*
Reference	*-*

Product Flags	
Grade: Not Assessable *Justification: These products do not contain flags, in their conventional form, and so this section of the maturity matrix has been graded as 'Not Assessable'.*	
Description	*The products do not contain flags in the conventional form (e.g., bit settings).*
Reference	*-*

3.1.4 Uncertainty Characterisation

Uncertainty Characterisation Method
Grade: Not Assessable

Justification: The methods used to characterise the uncertainties associated with geometric and radiometric calibration quality are not included in the documentation made available to users, and so this section of the maturity matrix has been graded as 'Not Assessable'.

Description	*(See above)*
Reference	*-*

Uncertainty Sources Included	
Grade: Basic *Justification: What has been provided, is an early analysis of the instrument performance. So, it is difficult to ascertain how what was found directly impacts the data supplied, which was collected several years later. Therefore, this section of the maturity matrix has been graded as 'Basic'.*	
Description	*(See above)*
Reference	*[RD-9] and [RD-10] Documentation not made available to users.*

Uncertainty Values Provided	
Grade: Not Assessable	
Description	*-*
Reference	*-*

Geolocation Uncertainty	
Grade: Basic *Justification: The geolocation uncertainty is discussed in [RD-6], in terms of both the stacking and orthorectification. However, there is no quantification. Therefore, this section of the maturity matrix has been graded as 'Basic'.*	
Description	*Uncertainty discussed, but no values provided.*
Reference	*[RD-6]*

3.1.5 Validation

It is important to note this section, relating to the 'Validation' column of the maturity matrix, is based on the results of the data quality assessments performed by the EDAP Optical team **only** (i.e. **independently** of any data quality assessments performed by the mission provider.

Reference Data Representativeness
Grade: Basic *Justification: The representativeness of the set of reference data, which refers to the exent (e.g. dynamic range, seasonal variation, geographical variation) to which reference measurements reflect the satellite measurements that they are being used to validate, is good (i.e. suitable) but the variety of reference data used (e.g. 'gold standard' reference mission sensor data, in-situ data) is relatively small, compared to what is available to the community, and so this section of the maturity matrix has been graded as 'Basic'.*

(Note, in general, increasing representativness requires that a variety of different reference datasets, to cover different observation conditions, be used.)	
Summary	*(See above)*
References	-

Reference Data Quality and Suitability	
Grade: Intermediate *Justification: The reference data quality and suitability used by EDAP comes with a single uncertainty value for the entire sensor mission and so this section of the maturity matrix has been graded as 'Intermediate'*	
Summary	*The data used as reference for the geometric calibration quality assessments include orthorectified panchromatic imagery from SPOT-5, which is validated by CNES as 2.5 m RMSE absolute accuracy.* *The data used as reference for the image quality assessments include orthorectified multispectral imagery from Pléiades.*
References	*[RD-11]*

Validation Method	
Grade: Intermediate *Justification: The validation methods used, despite being well-documented and used by the scientific community, produce simple uncertainty values (e.g., from a statistical distribution of results) and so this section of the maturity matrix has been graded as 'Intermediate'.*	
Summary	*The validation methods used to assess geometric calibration and image quality here, are all well-documented and used by the scientific community.*
References	*[RD-13], [RD-14]*

Validation Results	
Grade: Basic *Justification: The validation results, from validation assessment performed independently of those performed by the operator, show a reasonable agreement for the geometric assessment but the radiometric assessment could not be performed due to the lack of a radiometric calibration. Therefore, this section of the maturity matrix has been graded as 'Basic'.*	
Summary	*The validation results of all assessments are summarised in Section 4.*
References	*See Section 4 and 5.*

4. DETAILED NEMO-HD STILL IMAGERY QUALITY ASSESSMENTS

4.1 Objectives

The objective of this work is to assess all core aspects of sensor data quality (geometric calibration, radiometric calibration, image quality) against sensor and product performance requirements or specifications, using the sample of sensor products procured.

4.2 Geometric Calibration Quality

This section describes the assessment of geometric calibration quality, implemented by the processing chain, of sensor products in terms of **absolute geolocation accuracy**, **temporal geolocation accuracy** and **band co-registration accuracy**.

Table 4-1: NEMO-HD- Geometric Calibration Quality Assessment Product Sample

Product #	Product	Product Name	Sensor Viewing Angle (°)
1	La Crau (France)	NHDPCrau1 (20210325)	1.4
2	Salon-de- Provence (France)	NHD_Salon3 (20210701)	5.1

4.2.1 Absolute Geolocation Accuracy

4.2.1.1 Description and Method

The absolute (planimetric) geolocation accuracy of the orthorectified multispectral and panchromatic imagery was assessed using an image matching tool (based on a zero mean normalised cross-correlation algorithm, validated sub-pixel accuracy), provided by CNES, called the *MEDICIS / QPEC* tool [RD-12]. This determines the geometric displacement (i.e. accuracy) between the sensor's multispectral imagery (acting apparent location) and validated reference imagery (acting actual location), with a high geolocation accuracy, from a similar sensor (i.e., reference sensor).

This assessment was performed on the following product(s):

Product 1 (NIR band)

The orthorectified imagery included in this product has been used to determine the absolute geolocation accuracy over *relatively low and homogenous topography*, as the topography of La Crau does not exceed 190 m above the ellipsoid.

Product 2 (NIR band)

The orthorectified imagery included in this product has also been used to determine the absolute geolocation accuracy over *relatively low and homogenous topography* as the topography of Salon-de-Provence does not exceed 325 m above the ellipsoid.

Reference Product <SPOT-5>

The validated absolute accuracy of the orthorectified reference imagery, delivered by CNES as free from systematic and non-systematic errors (i.e. due to terrain relief), is < 2.5 m (RMSE) [RD-11]; the main contributor to this slightly degraded absolute accuracy was not the precision but actually the bias, which appeared to be systematic, of about 1.5 m. This information is of importance when using this reference imagery.

4.2.1.2 Results

The results of this assessment are detailed in Table 4-2.

Table 4-2 Absolute Geolocation Accuracy Assessment Results

Parameter / m	P1 PAN IM CL80	P1 MS NIR IM CL80	P2 PAN IM CL80	P2 MS NIR IM CL80
GCP Sample #[1]	192 /382	56/128	72/141	44/97
Mean Easting Error	0.79	-1.22	0.87	0.00
Mean Northing Error	-0.13	5.34	-1.71	-4.98
Easting Error Standard Deviation	6.33	10.95	6.80	12.46
Northing Error Standard Deviation	5.62	10.53	6.84	8.94
Easting Root Mean Square Error	6.38	11.02	6.86	12.46
Northing Root Mean Square Error	5.62	11.81	7.05	10.23
Root Mean Square Error	8.50	16.15	9.83	16.12
Circular Error @ 90%[2]	12.41	24.07	13.62	23.15

The results indicate the (average) absolute geolocation accuracy of orthorectified multispectral and panchromatic imagery is 23.61 m (4.22 MS pixels) CE90 and 13.02 m (4.65 PAN pixels) CE90, respectively. The slight degradation in the absolute geolocation accuracy, appears to be largely due to the precision (standard deviation, random error contribution) in both directions.

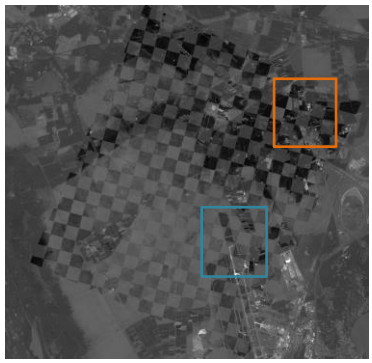
This result, however, should be considered with caution as image matching could only be performed here at a confidence level of 80 %[3], instead of the standard minimum of 95 %, due to factors such as the very small scene size and low contrast / radiometric resolution (originating from differences in viewing and solar geometries, radiometric resolution, spectral resolution and, the data is downscaled from 16-bit to 8-bit in order to match that

[1] *This refers to the number of pixels matched at the specified confidence level / the total number of pixels matched.*

[2] *It is common for the absolute geolocation accuracy to be described as a circular error at a specified percentile (e.g., CE90 means that a minimum of 90 % of the points measured have an error that is less than the stated CE90 value).*

[3] *Image matching is performed at a specified confidence level (e.g. if the confidence level is set at 95 % then the image matching results will be based on pixels that have been matched with 95% confidence / certainty).*

of the reference data). Therefore, the assessment was repeated but with another method that was based on the visual comparison of a generated checkerboard layer of the sensors imagery with a layer of the resampled reference imagery, to see if the aforementioned results could be verified.



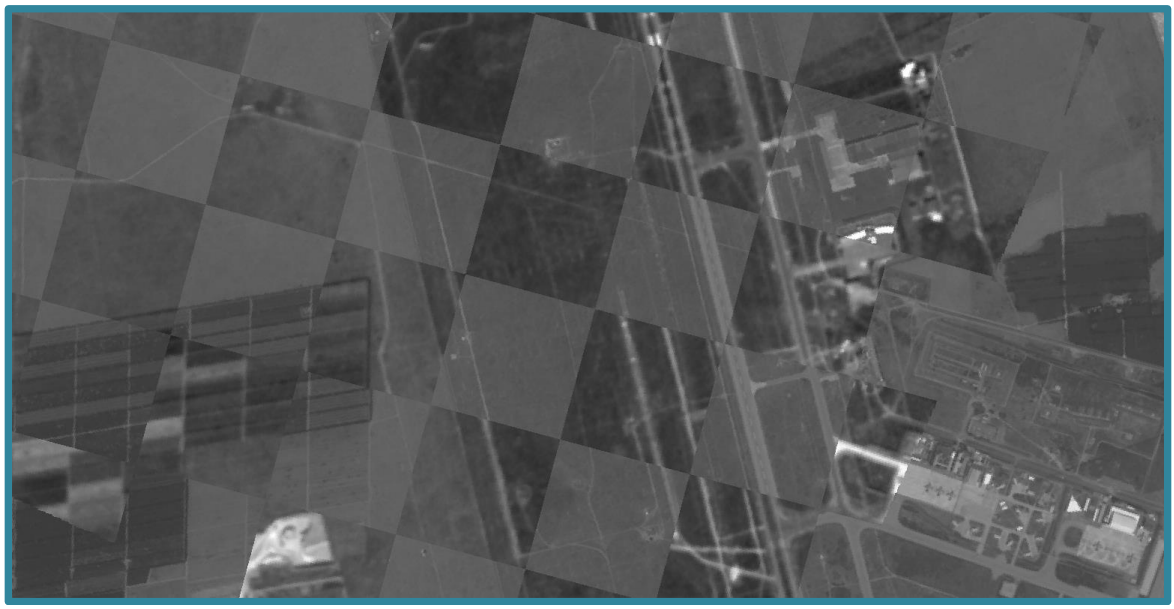


Figure 4-1 The assessment of absolute geolocation accuracy by the visual comparison of the generated sensor imagery (product 2 multispectral) checkerboard layer with the resampled reference imagery layer. Scale 1:14,000.

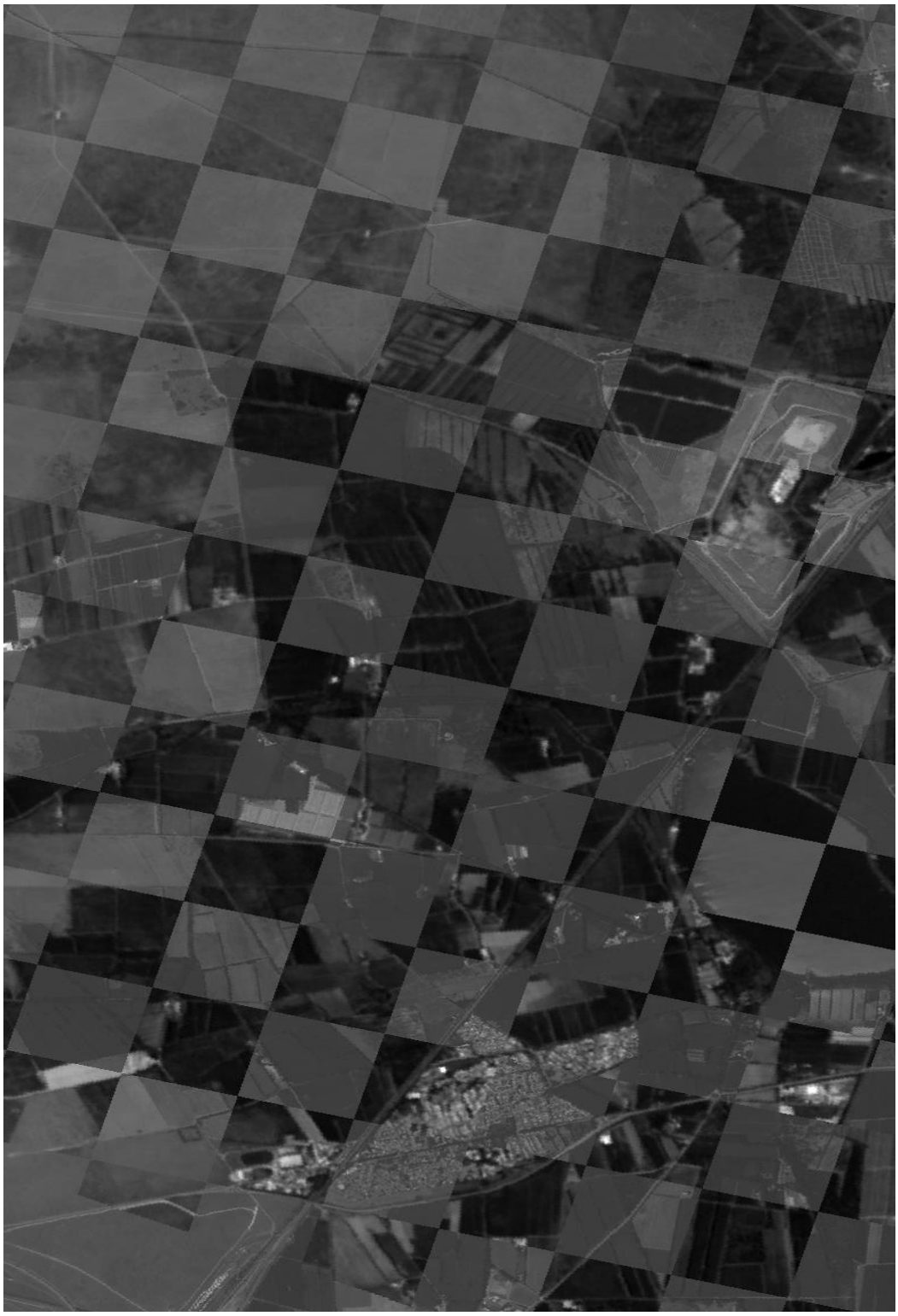


Figure 4-2 The assessment of absolute geolocation accuracy by the visual comparison of the generated sensor imagery (product 2, multispectral) checkerboard layer with the resampled reference imagery layer. Scale 1:14,000.

The results of the visual comparison indicate the absolute geolocation accuracy might be slightly lower than that determined using image matching; in Figure 4-1 and Figure 4-2, there is a non-systematic displacement, in both directions, of up five to six pixels when

visually comparing the locations of distinct features such as roads, road markings, field lines, etc.

4.2.2 Temporal Geolocation Accuracy

The temporal geolocation accuracy could not be assessed for this sensor due to the very small sample of suitable products procured.

Note there is no minimum performance requirement specified for band co-registration accuracy.

4.2.3 Band Co-registration Accuracy

The multispectral and panchromatic band co-registration accuracies have been determined using the aforementioned intensity-based image matching algorithm, where it was applied to the imagery of each pair of adjacent bands[4] (e.g., red **(band1)** and green **(band 2)**, green and blue **(band 3)**, blue and near-infrared **(band 4)**, near-infrared and panchromatic **(band 5)**).

This assessment was performed on the following product(s):

Product 1, 2

Note there is no minimum performance requirement specified for band co-registration accuracy.

4.2.3.1 Results

The results of this assessment are detailed in Table 4-3 and Table 4-4.

Note the spatial resolution of the panchromatic imagery was downsampled to match that of the multispectral imagery prior to image matching (relevant to image matching band pairs 4_5 and 5_1).

Table 4-3 Product 1 - La Crau: Multispectral and Panchromatic Band Co-registration Accuracy (Image Matching Confidence Level @ 95 %). Units: MS Pixels.

	Multispectral			Multispectral - Panchromatic	
	Band Pair: 1_2	Band Pair: 2_3	Band Pair: 3_4	Band Pair: 4_5	Band Pair: 5_1
Product 1					
# Matched Pixel Total	214/728	61/639	-	110/396	190/563
Mean Easting Error	-0.0129	1.6962	-	-1.3404	-1.8316

[4] *The band order is red, green, blue, nir and it is recommended that this information be included in the product metadata as well as the documentation (correction needed in as it indicates the opposite band order).*

Mean Northing Error	0.0124	1.2217	-	-0.6930	-0.0518
Easting Error Standard Deviation	0.4429	-0.5407	-	1.5504	1.4975
Northing Error Standard Deviation	0.4212	1.1945	-	1.6145	1.4435
Easting Root Mean Square Error	0.4431	1.7803	-	2.0495	2.3659
Northing Root Mean Square Error	0.4214	1.7086	-	1.7569	1.4444
Root Mean Square Error	0.6115	2.4676	-	2.6995	2.7719
Circular Error @ 90% (m / MS pixels)	**5.35 /0.96**	**20.93 /3.73**	**-**	**22.51 /4.02**	**23.32 /4.16**

Table 4-4 Product 2 - Salon-de-Provence: Multispectral and Panchromatic Band Co-registration Accuracy (Image Matching Confidence Level @ 95 %). Units: MS Pixels.

	Multispectral			Multispectral - Panchromatic	
	Band Pair: 1_2	Band Pair: 2_3	Band Pair: 3_4	Band Pair: 4_5	Band Pair: 5_1
Product 2					
# Matched Pixel Total	925 / 1465	515/1399	41/507	62/421	439/821
Mean Easting Error	0.1508	-0.1832	0.0101	-0.2980	-0.1799
Mean Northing Error	0.0349	0.1218	-0.6214	-0.2938	-0.2329
Easting Error Standard Deviation	0.2484	0.2467	0.7461	0.5047	0.3140
Northing Error Standard Deviation	0.1559	0.4438	1.0887	0.6026	0.6496
Easting Root Mean Square Error	0.2906	0.3073	0.7462	0.5861	0.3619
Northing Root Mean Square Error	0.1598	0.4602	1.2536	0.6705	0.6901
Root Mean Square Error	0.3316	0.5534	1.4588	0.8905	0.7793
Circular Error @ 90% (m / MS pixels)	**2.95 / 0.52**	**4.66 / 0.83**	**12.88 / 2.30**	**3.94 / 0.70**	**3.52 / 0.63**

The results of the band co-registration accuracy assessment for product 1 indicates the band co-registration accuracy is degraded (confirmed through the visual inspection of the bands extracted from the multispectral image). This result, however, is most likely due to the poor contrast levels, which occurs when many of the pixels in an image have brightness values within a narrow range of what is potentially detectable, seen in band 3 (see Figure 4-3). This would have had a significant impact on the efficacy of the image matching algorithm used to perform band co-registration during processing, and this appears to be evident in the results obtained for the co-registration accuracy of bands 2 and 4 with band 3 (see Table 4-3). It is well known that successful image matching is heavily reliant on good contrast levels (i.e. accurate image matching requires imagery with good contrast). Note the latter also explains why image matching could not be performed for band 3 and 4 of product 1 – the contrast levels are significantly different and so they could not be confidently matched.

The result of the band co-registration accuracy assessment for product 2, however, indicates the multispectral and multispectral-panchromatic bands are well co-registered (there is some room for improvement, if comparisons are made with similar, 'gold standard' sensors.).

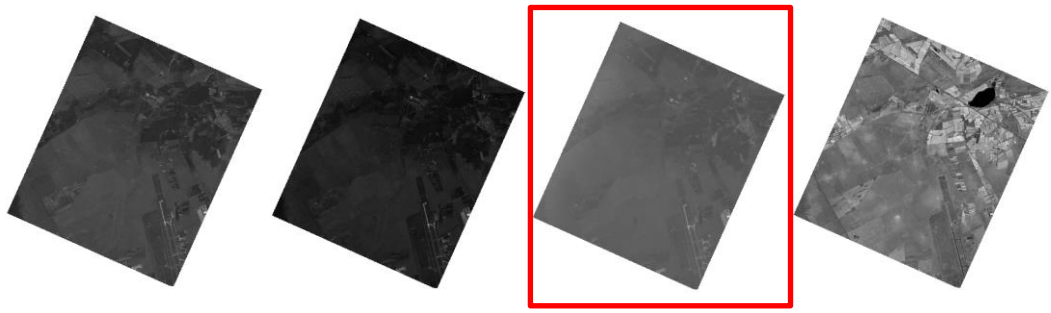


Figure 4-3 Product 1 (Left to Right - Band 1, Band 2, Band 3, Band 4)

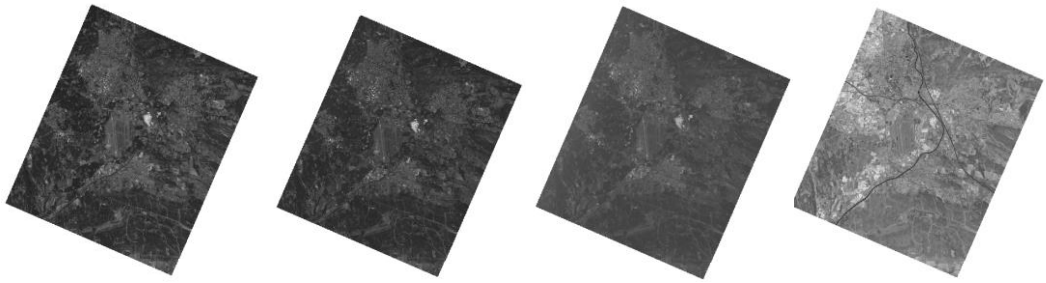


Figure 4-4 Product 2 (Left to Right - Band 1, Band 2, Band 3, Band 4)

In addition to the above, the error budget is computed (in this case, only for the multispectral bands), and it is based on the rule that per pixel displacement errors are transitive across all band pairs. By summing the displacement for all band pairs (e.g. (1, 2), (2, 3), (3, 4), (4,5)), the result is in the same order of displacement for the twin (1, 5), as shown in the equation below.

$$D_{1,5} \cong D_{1,2} + D_{2,3} + D_{3,4} + D_{4,5}$$

Where $D_{B,N}$ stands for displacement between the blue band and the NIR band (calculated for the easting and northing direction).

By comparing this estimate $(D_{1,5})$ against the true value $(D_{5,1})$ obtained with image matching, the error budget of the method is computed (i.e., error budget = $D_{1,5}$ + $D_{5,1}$ or $D_{5,1}$ -$D_{1,5}$). The results indicate the error budget, using product 2 as an example, in the easting direction is 0.14 MS pixels, which is much smaller than that in the northing direction that is 0.52 MS pixels.

4.3 Radiometric Calibration Quality

This section describes the assessment of radiometric calibration quality of sensor products, in terms of **absolute** and **temporal radiometric calibration accuracy**.

4.3.1 Absolute Radiometric Calibration Accuracy

This assessment could not be performed as the data has not been radiometrically calibrated.

4.3.2 Temporal Radiometric Accuracy

This assessment could not be performed as the data has not been radiometrically calibrated.

4.4 Image Quality

This section describes the assessment of product image quality on the supplied sensor products in terms of **Signal-to-Noise Ratio** (**SNR**), **Modulation Transfer Function** (**MTF**) and **Image Interpretability**.

Table 4-5 Image Quality Assessment Product Sample

Location	Product	Product Name
La Crau (France)	**1**	**NHDPCrau1 (20210325)**
Libya-4 (Libya)	**3**	**NHDLibija1 (20210529)**
Salon-de-Provence (France)	**2**	**NHD_Salon3 (20210701)**

4.4.1 Signal-to-Noise Ratio

This assessment has not been performed as the tool developed for this project currently expects only radiometrically calibrated (i.e. top-of-atmosphere radiance) data as input.

No minimum performance requirement has been specified by the operator for this metric.

4.4.2 Modulation Transfer Function

4.4.2.1 Description and Method

The modulation transfer function importantly describes the response of the imaging sensor as a function of spatial frequency, and so is strongly related to concepts such as sharpness, contrast and spatial resolution. Therefore, it is considered as an important image quality metric.

(It is important that this image quality metric be monitored post-launch or in orbit, not just pre-launch, in order to ensure that launch vibrations, transitions from air to vacuum, or changes in thermal state, have not degraded the sharpness of the optical.)

The products used for this assessment include:

Product 2 (Panchromatic band only)

Unfortunately, a sample product that was generated from a lower processing level could not be procured for this assessment (higher processing levels introduce smoothing effects and therefore degrades the true MTF).

This assessment has been performed using an open-source tool, validated against third party software, made publicly available at https://github.com/JorgeGIIG/MTF_Estimator. The tool, accompanied by detailed documentation that includes information on the algorithm (Slanted-Edge methodology based) used, works in the following way:

1. Select a band and create a shapefile which defines the target edge to be used:
    a. The target edge must be straight and sharp (a man-made target is more likely to have these features) and defined by uniform high and low reflectance surfaces.
    b. The target edge must be vertical (i.e., the angle is important). This is an important requirement related to how the algorithm works - if an along track or across-track assessment is needed then the image can be rotated accordingly.
2. Run the tool
    a. The data in each transect (each image row), defined by the shapefile, is smoothed and then differentiated in order to obtain a coarse estimation of the pixel position of the target edge. The latter estimation is then used to set the initial conditions of the optimisation technique which is used to fit a sigmoid function to the data (as shown in Figure 4-5).

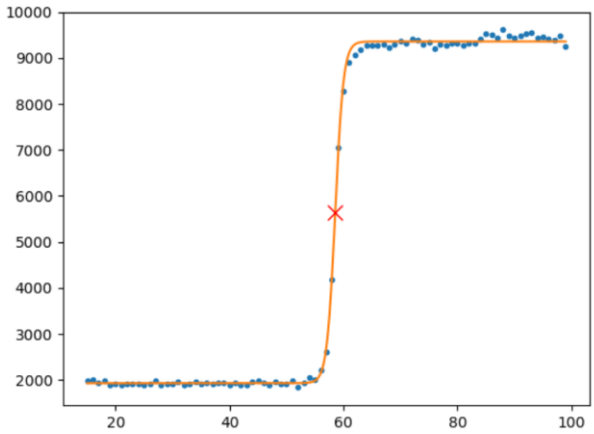


Figure 4-5 An example of the sigmoid function (-) is fitted to the data (•) in a transect. The point of inflexion (x) shows the estimated sub-pixel edge position. X axis is pixels, y axis is digital numbers

    b. The estimated sub-pixel position data for all transects is subjected to linear regression in order to ensure the target edge is straight as assumed (any outliers are removed during this process) and the target edge angle estimated.
    c. The estimated sub-pixel edge position is used to shift each transect to a common origin, hence creating a supersampled virtual edge which is modelled as a spline and thus a representation of the Edge Spread Function (**ESF**).
    d. The (two-dimensional) Point Spread Function (**PSF**) is obtained by fitting the spline shape to a one-dimensional Gaussian function (Line Spread Function) using Levenberg-Marquardt optimisation.
        i. The PSF defines the apparent shape of a point target as it appears in the resulting image: it is therefore directly related to the sharpness of images provided by the sensor / imaging system.
    e. The MTF is then estimated from the modulus of the Fourier transform of the PSF.
        i. The MTF informs on the contrast of the different spatial frequency components of the observed image.

Note the minimum performance requirement has not been specified for this metric by the operator.

4.4.2.2 Results

The results of this assessment are included in Figure 4-7. Note this assessment was also performed on the panchromatic imagery provided of the target in Baoutou (China) and the results were similar.

Figure 4-6 Salon-de-Provence Artificial MTF Target: MTF Assessment of NEMO-HD (Panchromatic band only).

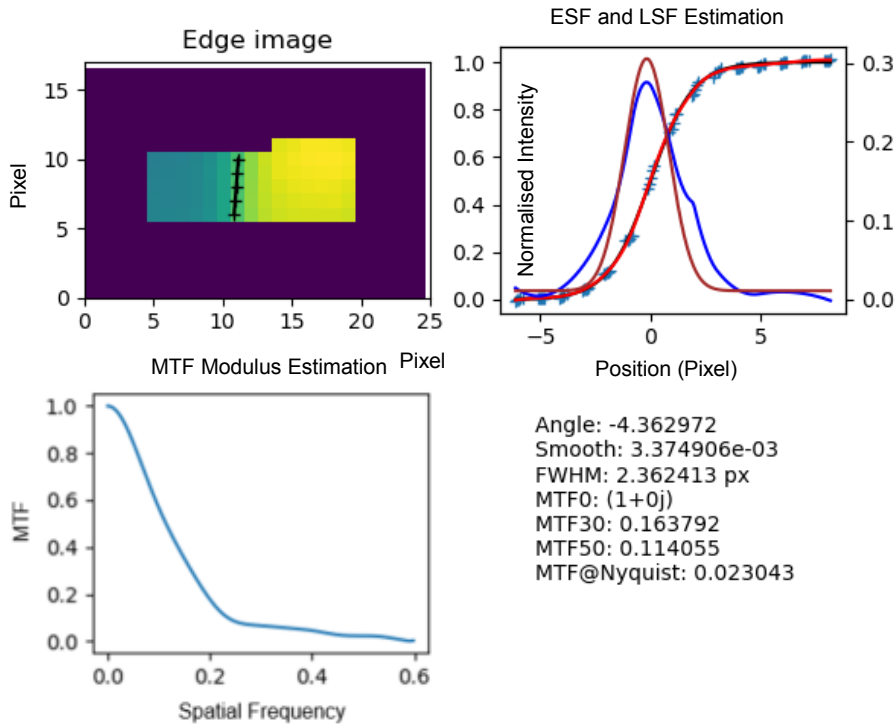


Figure 4-7 MTF results for Salon-de-Provence MTF target (Along-track Profile). The (top left) transects successfully used to detect the sub-pixel location of the edge (i.e. supersampled edge), (top right) supersampled edge (light blue), the best-fit Gaussian resulting from the optimisation used (brown), optimised ESF spline

numeric model (red) and optimised PSF spline numeric model (blue). The (bottom left) the MTF modulus estimation.

Note the across-track edge, between the black and white boxes of the MTF target, could not be detected by the tool.

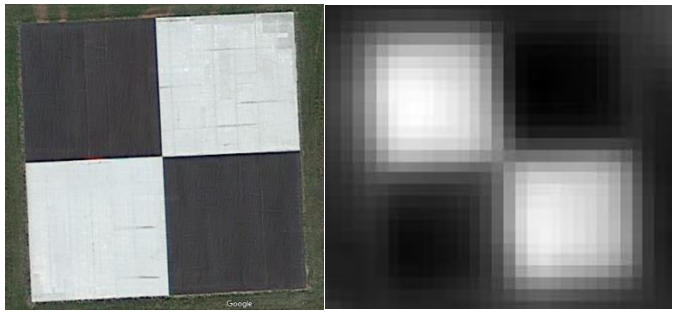


Figure 4-8 The artificial MTF target in Salon-de-Provence (Google (Left), NEMO-HD PAN (Right)).

The results of this assessment indicate the following:

- The nominal spatial resolution of the panchromatic band is 2.8 m and the effective spatial resolution determined by the mission provider, which is estimated using the Full Width at Half Maximum (**FWHM**) of the PSF, is 3.14 m [RD-3]. The effective spatial resolution determined by this assessment is 6.60 m.
- The MTF@N_f is 0.02.
    - The sampling period or frequency is usually defined by the ground sampling distance or by the corresponding Nyquist frequency (N_f), which is defined as half the inverse of the ground sampling distance (for example, for NEMO-HD Pan N_f = 0.18). Given a ground sampling distance, the N_f essentially corresponds to the highest spatial frequency that can be represented by the imaging system (i.e. signals with spatial frequencies higher than N_f cannot be reliably reproduced and can cause aliasing).
    - The MTF@N_f determined by the assessment of this imagery indicates the MTF is lower than the MTF@N_f determined pre-launch (post-launch estimate is not documented) [RD-3, RD-10].

However, it is important to note that the results of this type of assessment is sensitive to differences in the observation conditions, atmospheric conditions, post-processing (e.g. products of higher processing levels generally use resampling kernels that can have a smoothing effect and can degrade MTF), etc. It is most likely the mission provider performed this assessment using basic imagery (ideal) instead of orthorectified imagery as done so here.

4.4.3 Image Interpretability

4.4.3.1 Description and Method

The image interpretability of optical sensor imagery is an important aspect of image quality (originating from the actual sensor or image processing), especially in terms of their practical use or application. This is commonly assessed, subjectively, using a well-defined procedure that is based on the successful interpretation of objects or features (points) of

interest according to the National Imagery Interpretability Rating Scale[5] (**NIIRS**) category in which the sensor belongs. This well-defined procedure also importantly allows for the cross-comparison of image quality from similar sensors.

The product(s) used for this assessment are the following:

Product 2

Reference Product: <Pléiades>

The objects or features of interest used for this assessment are deemed suitable for **NIIRS Category 2 (4.5 – 9.0 m GSD)** and **NIIRS Category 3 (2.5 – 4.5 m)** imagery.

The method used to assess image interpretability consists of the visual inspection of suitably sized clips of the sensor's imagery, for all bands, centred on the points of interest (**POI**) listed in Table 4-6. If the latter can be successfully detected, at the very least, then image interpretability is considered as good.

Note comparisons are made with clips from a 'gold standard' reference mission (e.g., Pléiades High-Resolution (**PHR**) imagery (bands 1 - 3 only)), following downsampling of the spatial resolution to match the spatial resolution of NEMO-HD, also.

Table 4-6 Image Interpretability: POI in Salon-de-Provence.

wkgt_geom (UTM 31)	ID	Description
Point (671090.3105554151115939 4830278.58671295549720526)	1	Modulation Transfer Function target
Point (671364.24309313111007214 4833044.0252351425588131)	2	Motor way / sharp transition (45° NE)
Point (668580.81736886233557016 4828965.45189037173986435)	3	Forest
Point (670056.62237295764498413 4828905.08180973120033741)	4	Roundabout / parking lot
Point (669985.90922565956134349 4832120.72269264236092567)	5	Elevated tree
Point (669956.03863696497865021 4832655.53592716064304113)	6	Motor way / roundabout
Point (670564.24590074480511248 4833363.40447467099875212)	7	The dam
Point (669836.88448120269458741 4832528.00618595350533724)	8	Big building (shadow)
Point (670518.95015854423400015 4829513.56928175128996372)	9	Landing track - 34
Point (670249.72702971810940653 4831735.0312919020652771)	10	Floor painting
Point (670900.38168655894696712 4829617.21182315889745951)	11	Crop fields / sparse

[5] https://irp.fas.org/imint/niirs.htm

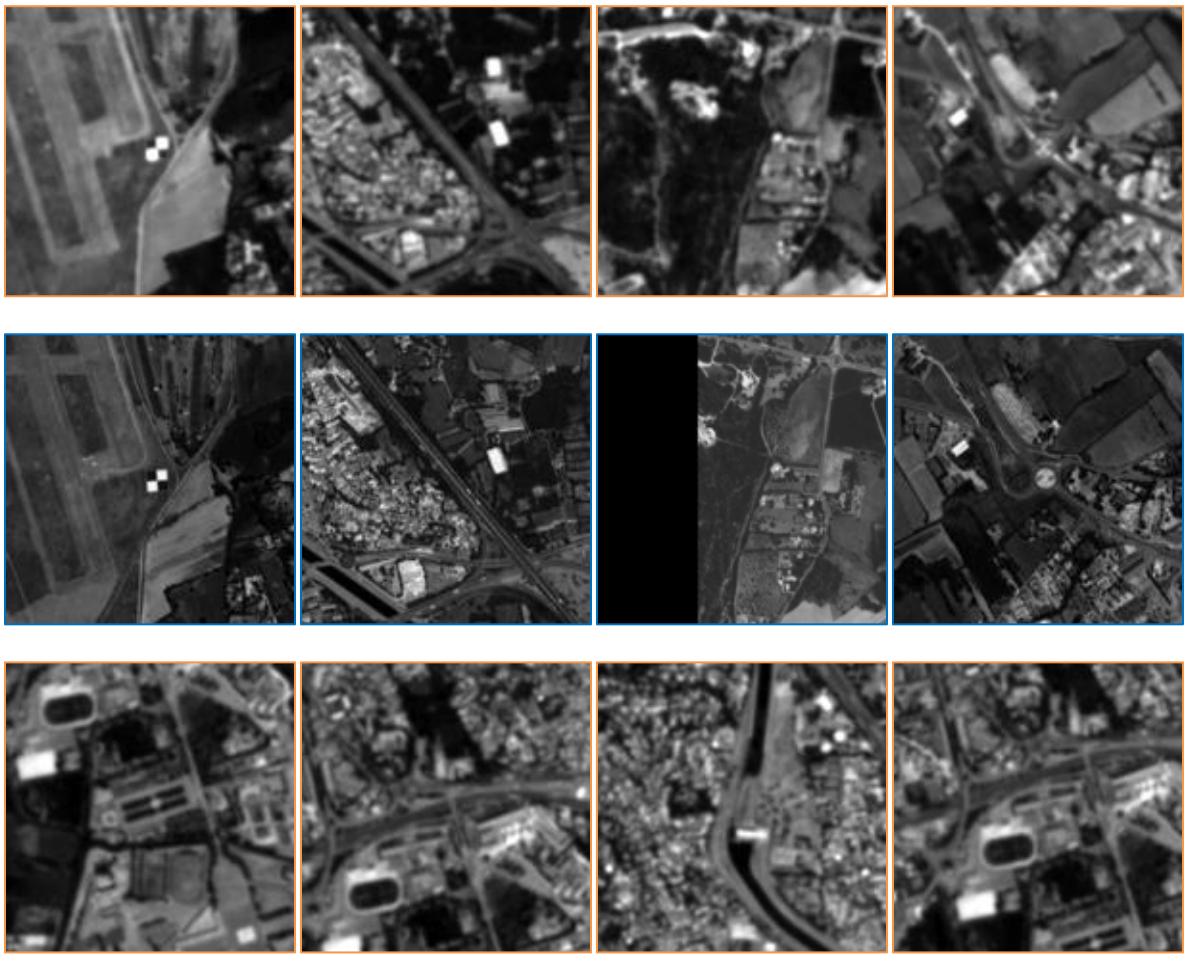
wkgt_geom (UTM 31)	ID	Description
Point (671548.0352310094749555 4830292.1131860688328743)	12	Broad-leaved woodland
Point (671099.93821095407474786 4828090.14610077627003193)	13	Crop fields
Point (671156.44116920174565166 4828825.77096180152148008)	14	Bridge and water
Point (671120.4438803291413933 4827691.31545618735253811)	15	Crop fields
Point (670328.31568091106601059 4831489.30539688002318144)	16	Building / EA 15
Point (671516.86161747551523149 4833207.41657157335430384)	17	Greenhouse
Point (669996.87127304612658918 4829099.09009433817118406)	18	Parking lot
Point (670062.87681329366751015 4829781.35287734866142273)	19	Plane parking
Point (670860.46870227111503482 4831527.10888031311333179)	20	Plane hangar
Point (671246.59432400949299335 4832300.03732818737626076)	22	Urban city

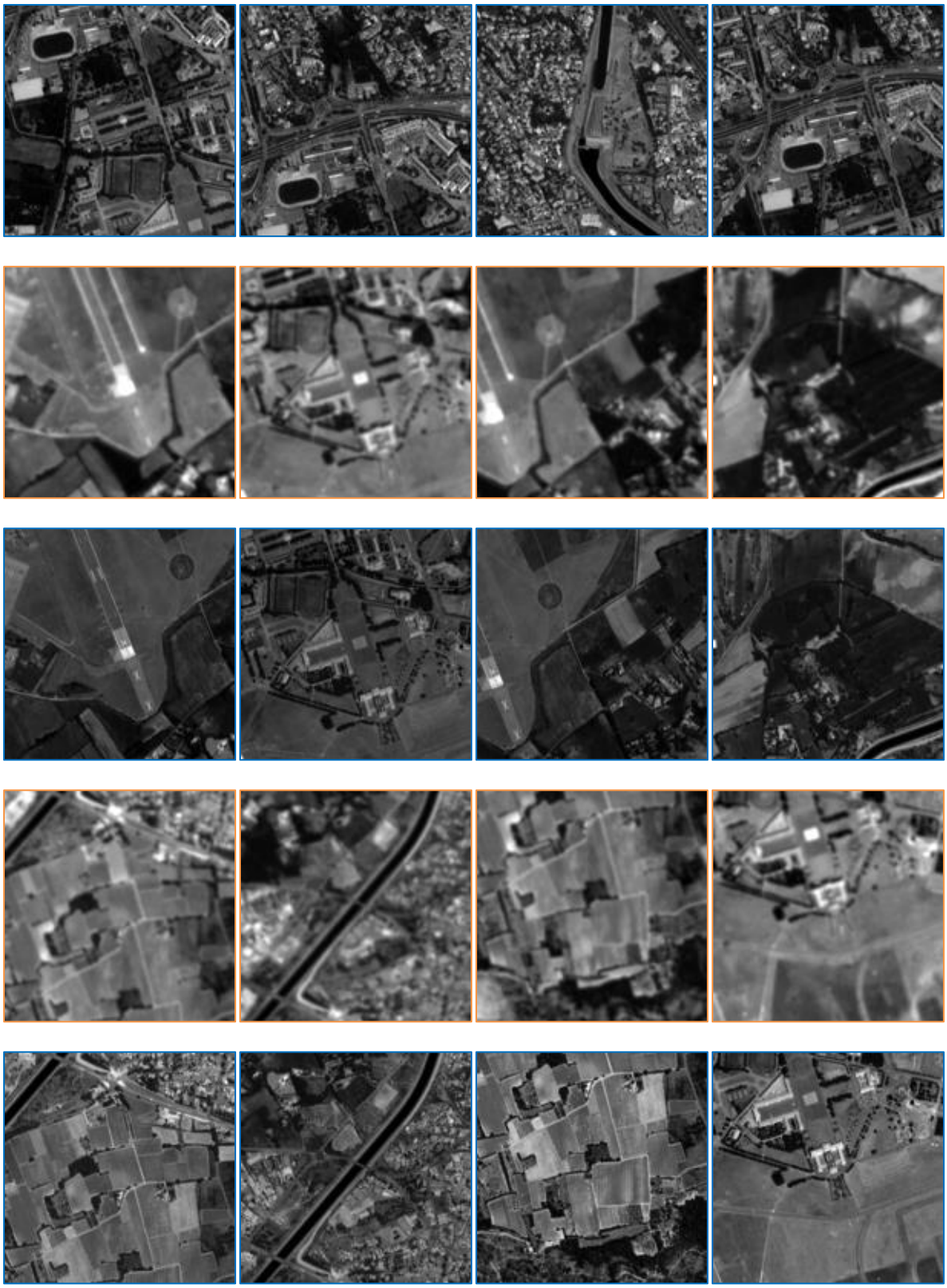
4.4.3.2 Results

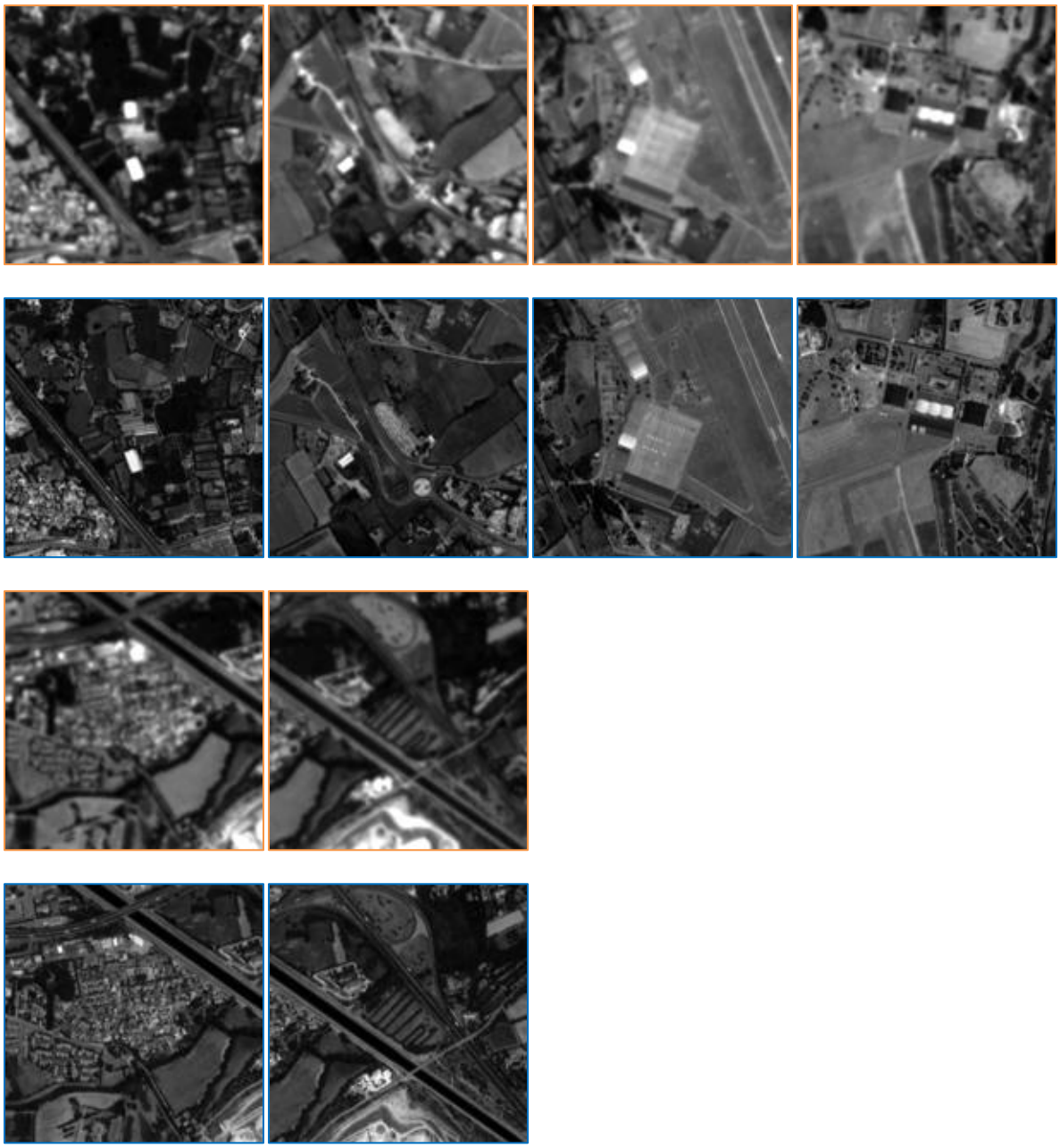
The results generally indicate the objects or features of interest can be delineated in the multispectral and panchromatic imagery, as shown in the figures below, but this can be improved upon with the improvement of image quality (via post-processing). The latter is based on comparisons with reference multispectral imagery (visible bands only), from Pléiades (superior image quality, expected of a 'gold standard' sensor), whose spatial resolution has been downsampled to match that of the multispectral imagery from NEMO-HD.

Note this assessment takes into account that the contrast is different between the imagery from the two sensors, which is expected as the two sensors having different ranges (due to different spectral characteristics), and so is considered as only a minor disadvantage to using this particular method.

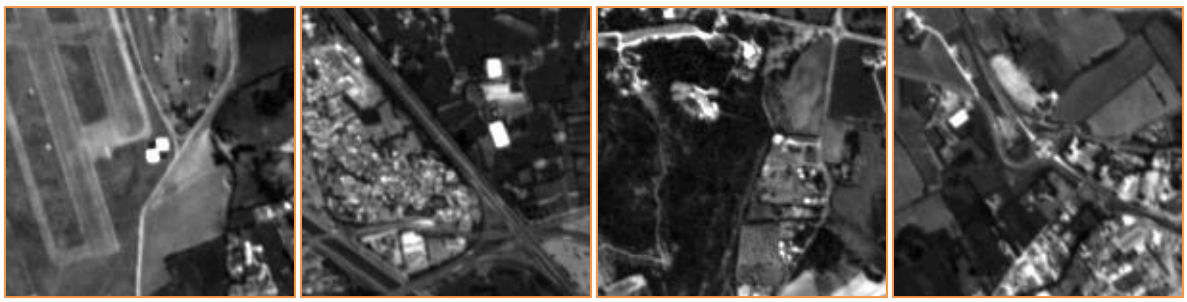
Band 1 (NEMO-HD (Red) , Pléiades (Red), Points 1 - 21)

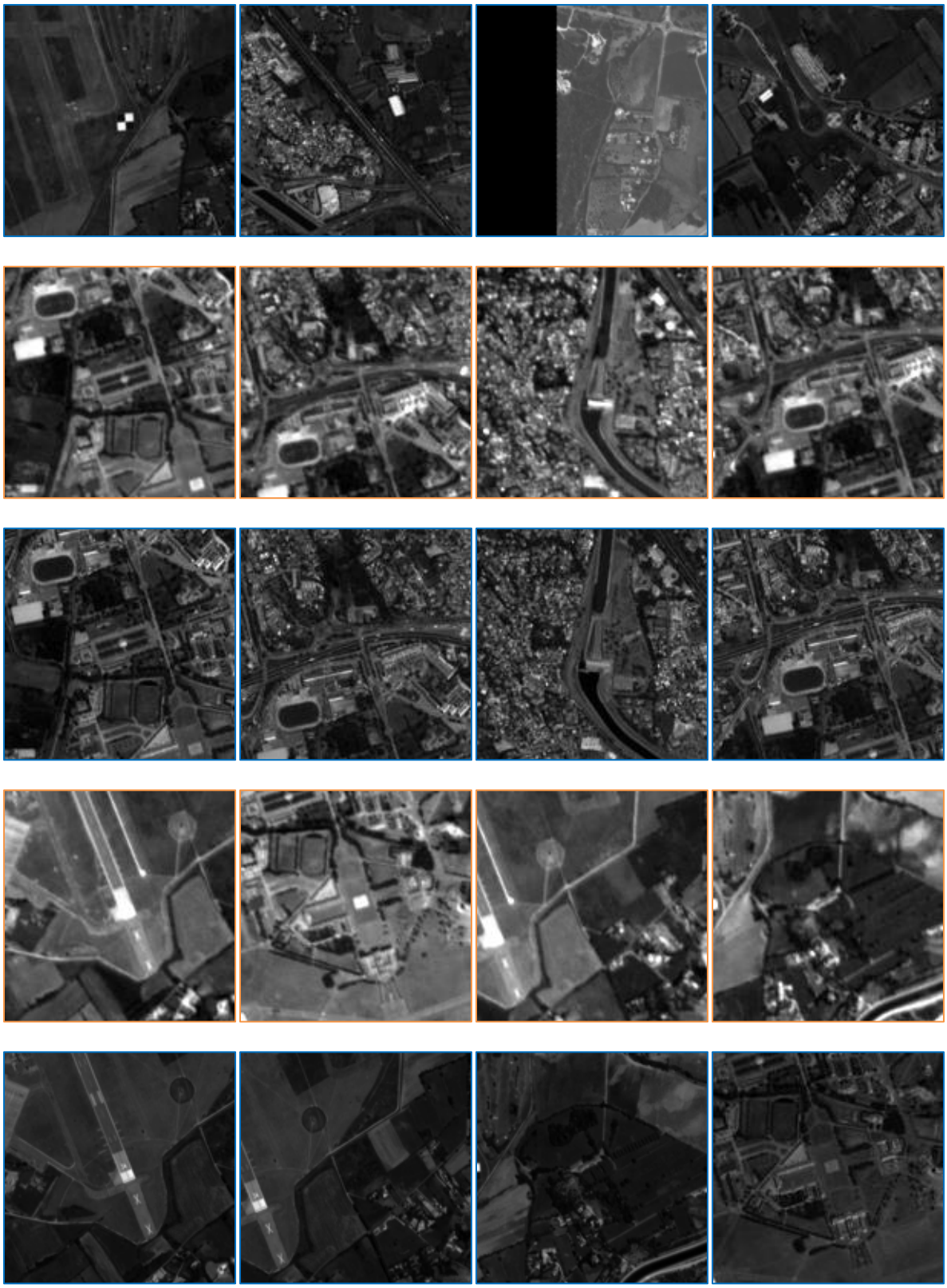


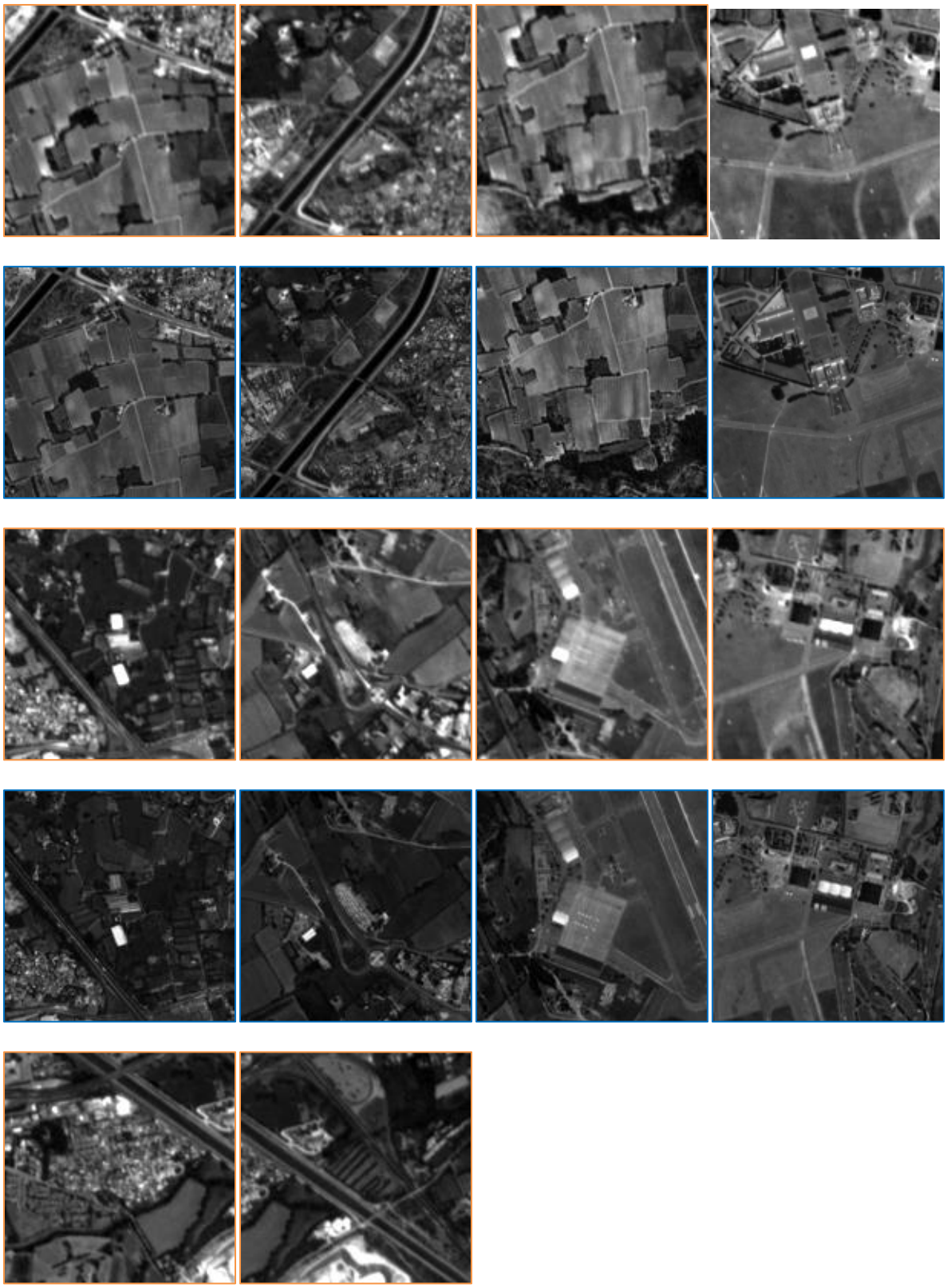


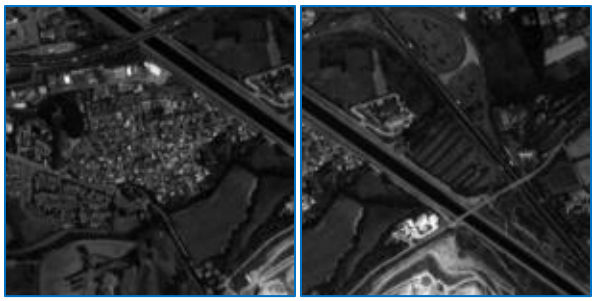


Band 2 (NEMO-HD (Green), Pléiades (Green), Points 1 - 21)

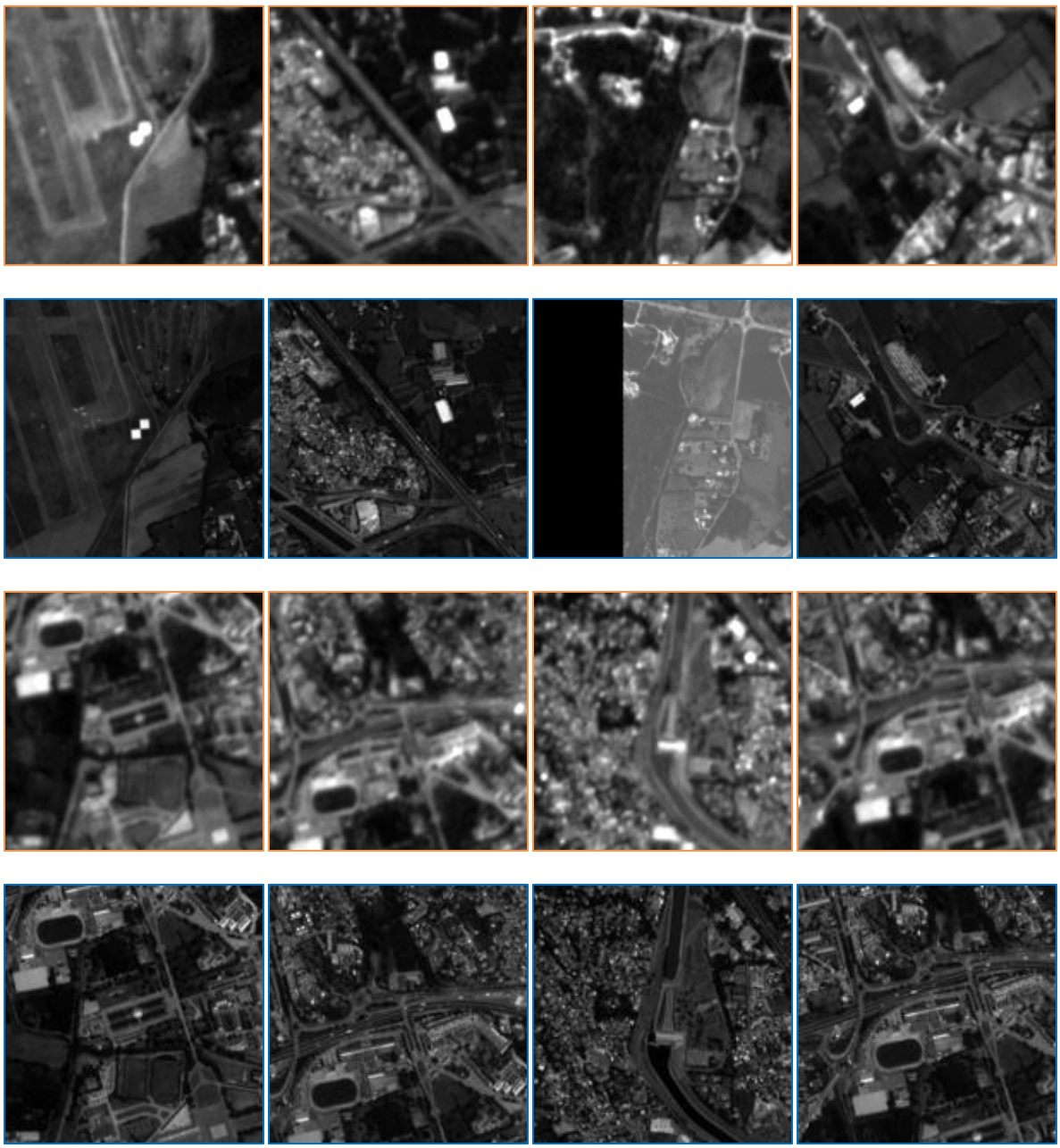


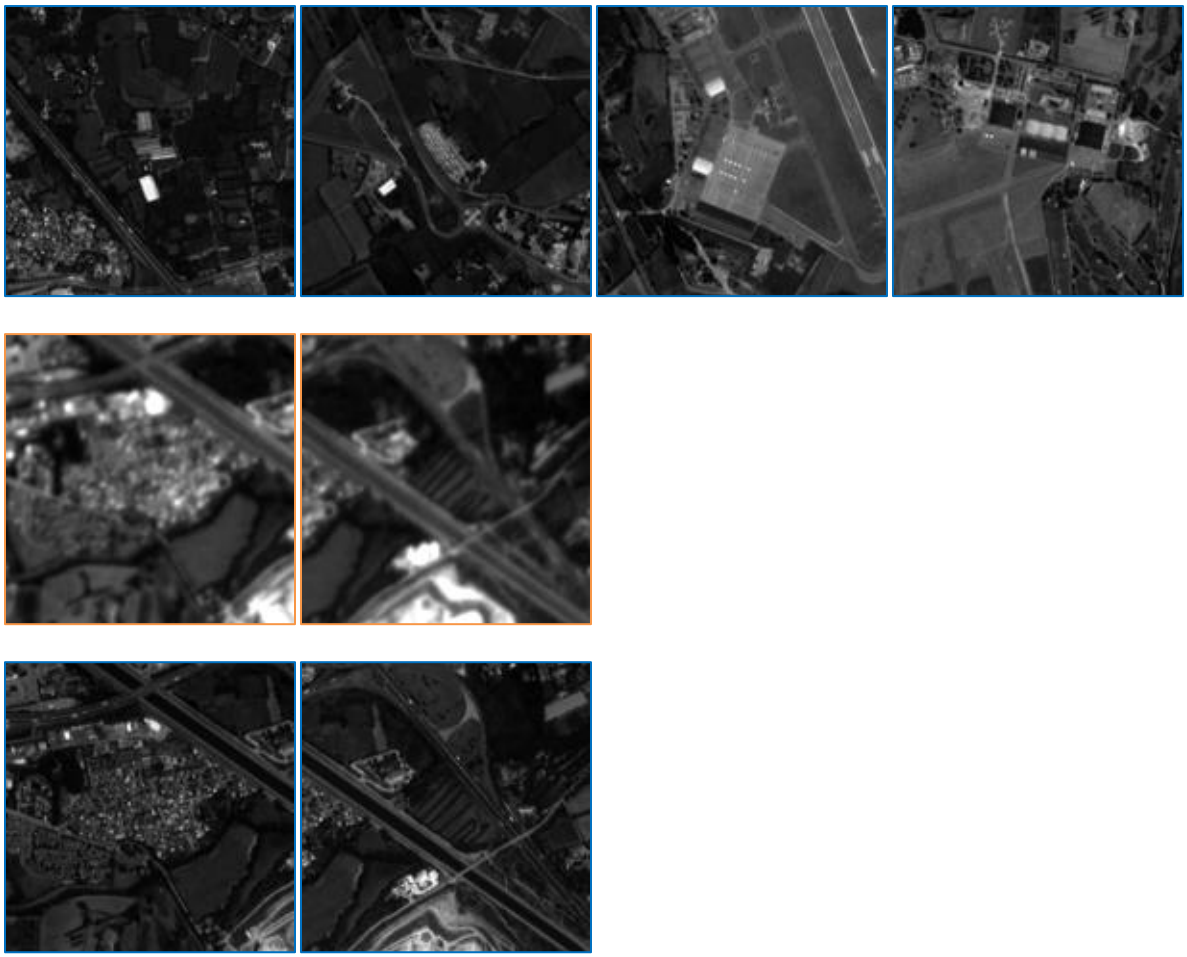




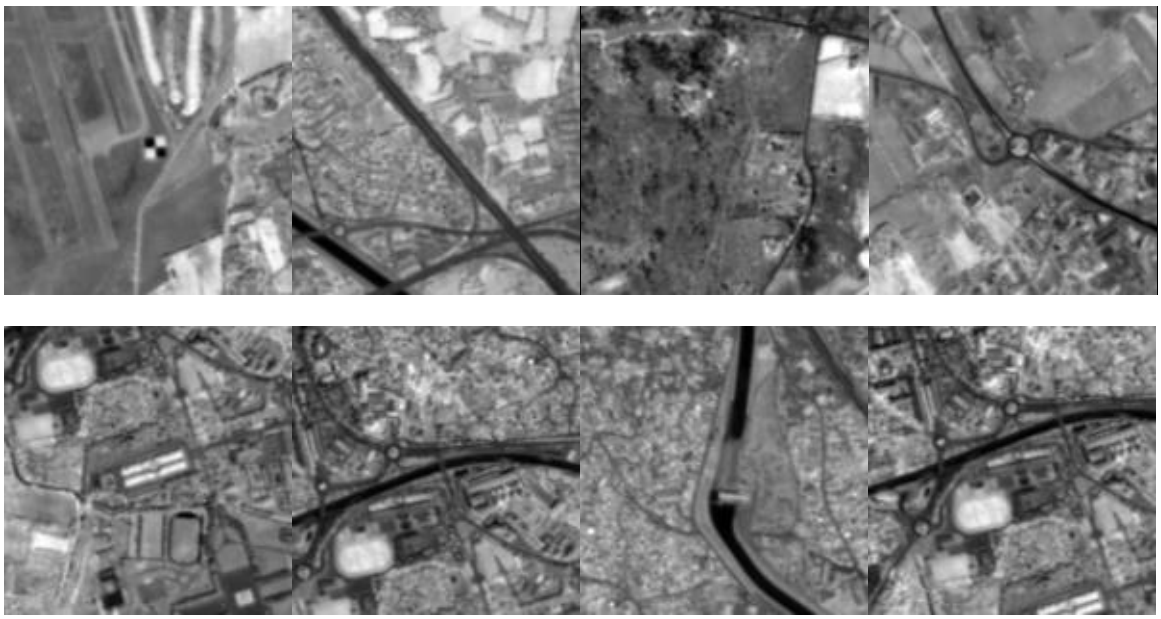


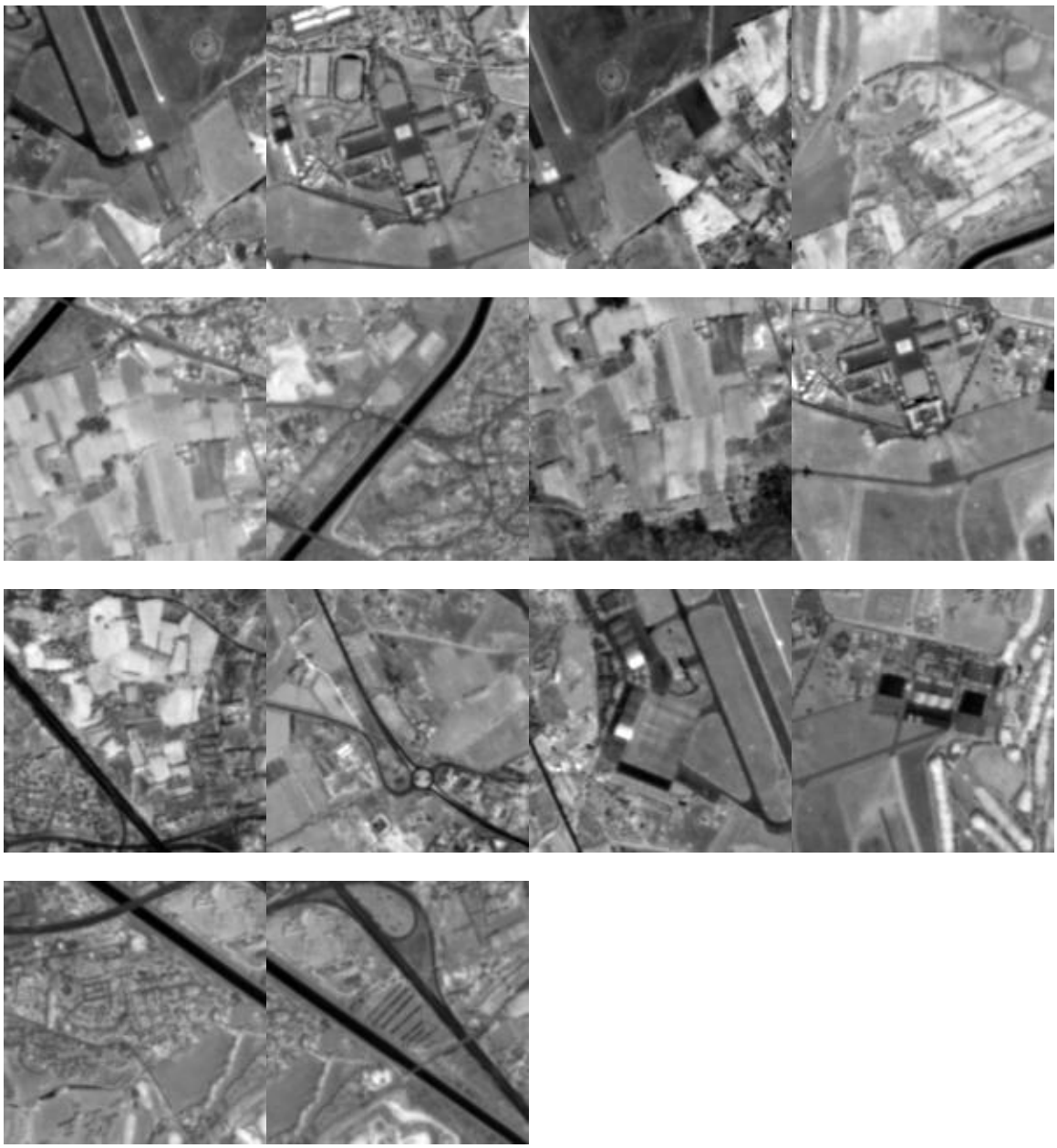
Band 3 (NEMO-HD (Blue), Pléiades (Blue), Points 1 - 21)



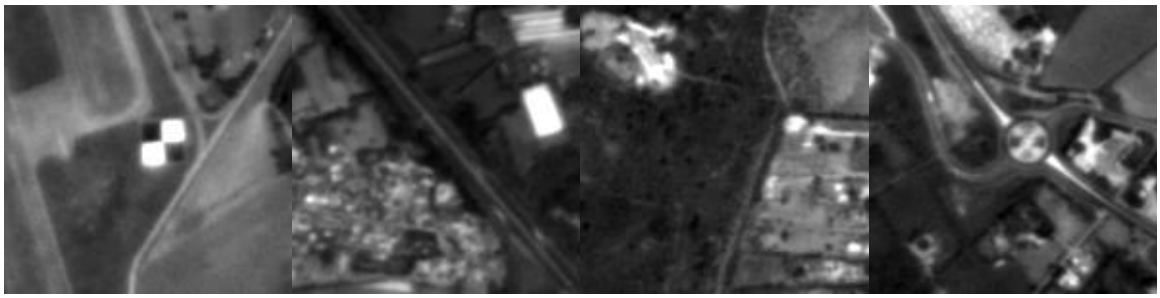


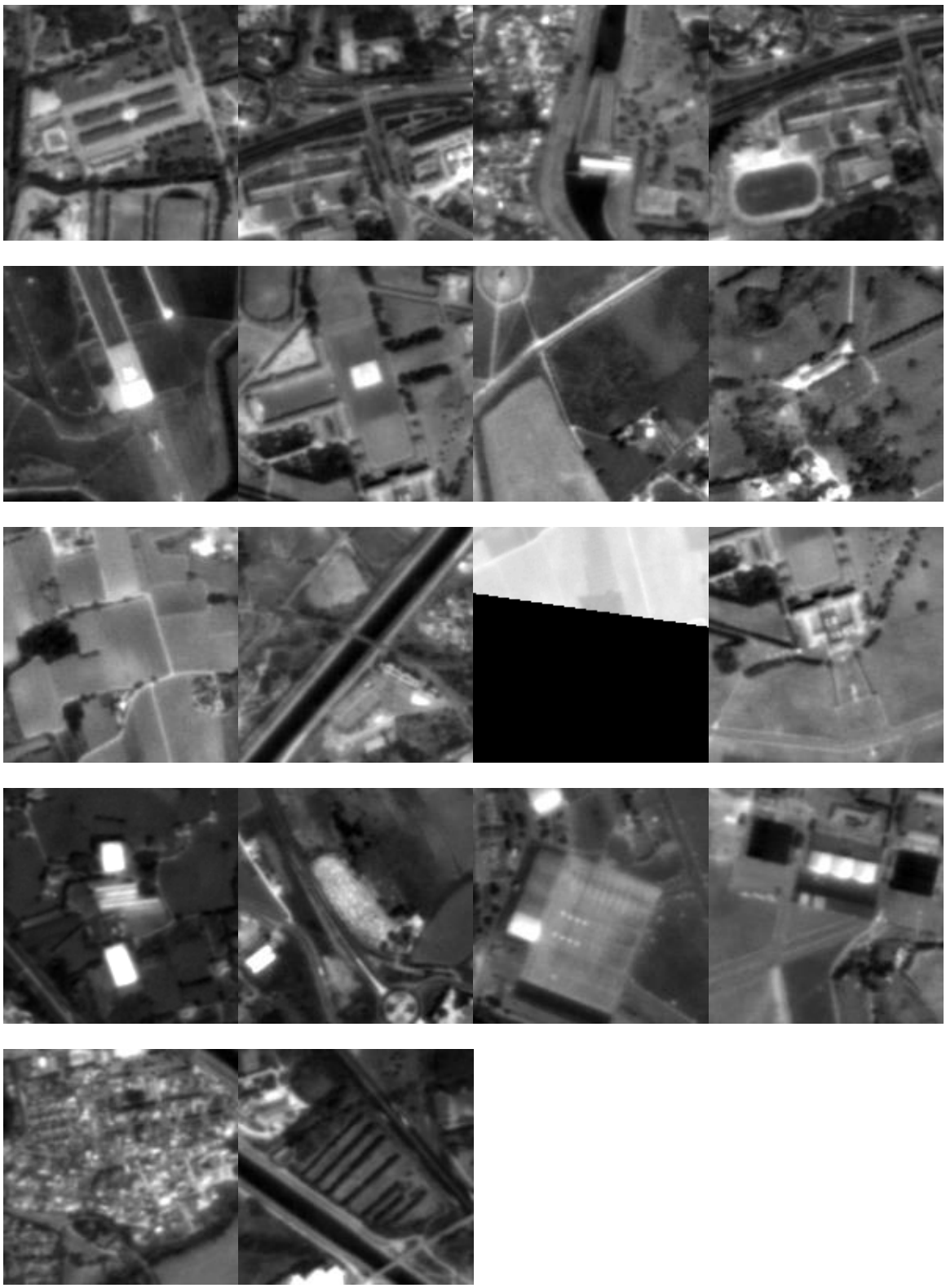
Band 4 (NEMO-HD, Points 1 - 21)





Band PAN (NEMO-HD, Points 1 - 21)





4.5 Visual Inspections

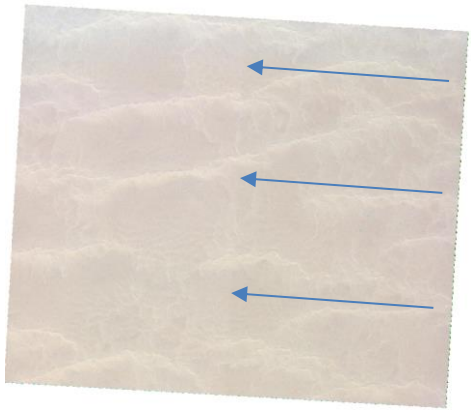
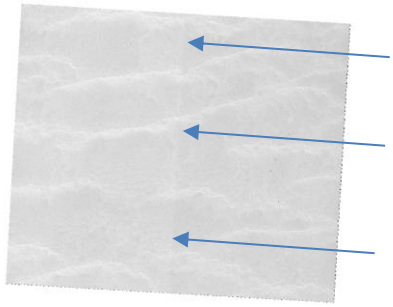
4.5.1 Description and Method

General visual inspections were performed on the multispectral and panchromatic imagery included in all products procured, despite not all being used in the previous assessments, in order to ensure there were no anomalies or artefacts present.

Note the visual inspections of the product imagery also include inspections of their histograms (e.g., to support detection of anomalies or artefacts in the imagery, including saturation) and product metadata.

4.5.2 Results

Product	Visual Inspection Results	
1	**Location**: Baotou (China) **Product Name:** NHDTargetCN2_42D_MS_ortho **Comment**: The product imagery does not appear to contain any major anomalies or artefacts. Note the multispectral imagery produced by this sensor contains vignetting in the blue band (the mission provider aims to have this corrected in the near future) [RD-3].	
2	**Location**: La Crau (France) **Product Name**: NHDRCrau1_35M_ortho **Comment**: The product imagery does not appear to contain any major anomalies or artefacts.	

3	**Location**: Libya **Product Name**: NHDLibija1_40D_MS_ortho **Comment**: The product imagery does not appear to contain any major anomalies or artefacts. Note there is a line in the along-track direction that is evident in imagery produced by this sensor, especially in imagey of bright and homorogenous areas. This is due to channel readout (each multispectral channel has two readouts, left and right, with slightly different offsets and gains that are currently being accurately characterised by the mission provider) [RD-3].	 (no stretching applied) 

4	**Location**: Salon-de-Provence (France) **Product Name**: NHD_Salon3_37D_MS_ortho **Comment**: The product imagery does not appear to contain any major anomalies or artefacts.	

5. CONCLUSIONS

This technical note details the high-level data quality assessments (including geometric calibration, radiometric calibration and image quality) that were performed on a very small sample of **orthorectified NEMO-HD bundle products**. The results of the aforementioned data quality assessments conclude that the current data quality is good (geometrically only, as the data is not yet radiometrically calibrated) but there is still room for improvement (e.g. radiometric calibration, more detailed user documentation) as the processing chain and products are not yet mature.

APPENDIX A NEMO-HD TEST DATASET

ID	Site	Product_Identifier
1	La Crau (France)	NHDPCrau1 (20210325)
2	Salon-de- Provence (France)	NHD_Salon3 (20210701)
3	Libya-4 (Libya)	NHDLibija1 (20210529)

Example of product metadata contents:

<Header>1.0</Header>
<CompletionFlag>1</CompletionFlag>
<Identifier>NHD_Salon3_37D_MS_ortho.tif</Identifier>
<AcquisitionDate>2021-05-29 09:01:31.016000+00:00</AcquisitionDate>
<SatId>NEMOHD</SatId>
<ObservationID>37D</ObservationID>
<ChannelID>MS</ChannelID>
<NumBands>4</NumBands>
<NumRows>2441</NumRows>
<NumColumns>2146</NumColumns>
<BitsPerPixel>16</BitsPerPixel>
<ProductType>L3</ProductType>
<OutputFormat>GeoTIFF</OutputFormat>
<CompressionType>Downlink</CompressionType>
<CoordinateSystem>WGS84</CoordinateSystem>
<Extent>
<ULLon>5.0493903016052695</ULLon>
<ULLat>43.669912611479695</ULLat>
<URLon>5.1938775091926965</URLon>
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</Extent>
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<ExposureDuration>N/A</ExposureDuration>
<MeanCollectedGSD>5.6</MeanCollectedGSD>
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<MeanSunEl>63.85169312162116</MeanSunEl>
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<MeanInTrackViewAngle>0.8</MeanInTrackViewAngle>
<MeanCrossTrackViewAngle>-5.0</MeanCrossTrackViewAngle>
<MeanOffNadirViewAngle>5.1</MeanOffNadirViewAngle>
<CloudCover>N/A</CloudCover>
<FocalLength>0.36012</FocalLength>
<DetPitch>3.45</DetPitch>
<Gain>0.0</Gain>
<Offset>0.0</Offset>

[END OF DOCUMENT]