Technical Note on Quality Assessment for Maxar WorldView-3 HD

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AMENDMENT RECORD SHEET

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

ISSUE	DATE	REASON
0.1	04 01 2022	First draft
0.2	21 04 2022	Second draft, addressing comments from ESA and Maxar.
1.0	29 06 2022	First issue

TABLE OF CONTENTS

1. INTRODUCTION

This technical note details the results of the data quality assessments, including geometric calibration, radiometric calibration and image quality, performed on a sample of commercial *Maxar WorldView-3 (**WV3**) High Definition (**HD**)* products that have been procured from the data provider, *European Space Imaging* (**EUSI**).

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 *Earth Observation* (**EO**) *Mission Data Quality Assessment Framework*. An important representation of this framework, constructed by the National Physical Laboratory (**NPL**), is what is known as the *Maturity Matrix*. It is a diagrammatic summary of the following:

- ***Documentation Review**: the EDAP optical team reviews resources (e.g. ancillary data and documentation) provided by the mission provider (data provider and / or operator), 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).*

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

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

It is important to note the purpose of the aforementioned framework is to ensure 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. EDAP.REP.002 Optical Mission Quality Assessment Guidelines, 1.0, 16 October 2019.

RD-3. Formellar, C., Introducing HD: See More, Do More with High-Definition Imagery, Available at: https://blog.maxar.com/leading-the-industry/2020/introducing-hd-see-more-do-more-with-high-definition-imagery, 24 July 2020.

RD-4. European Space Imaging 15 cm HD Data Sheet, Available at: https://www.euspaceimaging.com/wp-content/uploads/2020/11/Data-Sheet-15cm-HD-final-1.pdf

RD-5. Gleason, M/., Maxar - HD Satellite Imagery and Machine Leaning More Accurately Detect and Locate Features of Interest with Greater Consistency, Available at: https://blog.maxar.com/earth-intelligence/2020/hd-satellite-imagery-and-machine-learning-more-accurately-detect-and-locate-features-of-interest-with-greater-consistency, 21 October 2020.

RD-6. Geller, C., Five Features Required to Turn Satellite Imagery into Analysis-Ready Data, Available at: https://blog.maxar.com/leading-the-industry/2021/five-features-required-to-turn-satellite-imagery-into-analysis-ready-data , 24 February 2021.

RD-7. Maxar - Absolute Radiometric Calibration, The Baseline for Success (13264_102978826.pdf), Available at: https://www.maxar.com/resources or here.

RD-8. Maxar Map-Ready Imagery Data Sheet, February 2021, Available at: https://maxar.com/products/optical-imagery (13264_94721903_4.pdf).

RD-9. WorldView-3 Data Sheet, May 2017, Available at: https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/95/DG2017_WorldView-3_DS.pdf.

RD-10. Maxar - Accuracy of WorldView-3 Products, Available at: https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/38/DG_ACCURACY_WP_V3.pdf.

RD-11. WorldView-3 Absolute Radiometric Calibration: 2016v0, updated 6 June 2017, Available at: https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/209/ABSRADCAL_FLEET_2016v0_Rel20170606.pdf.

RD-12. Maxar - Radiometric Use of WorldView-3 Imagery, v2.0, 22 February 2016, Available at: https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/207/Radiometric_Use_of_WorldView-3_v2.pdf

RD-13. 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-14. Kuester, M., Ochoa, T., Mazar – Absolute Radiometric Calibration Is An Essential Tool to Imagery Science But What Is it?, 2020, Available at: https://blog.maxar.com/tech-and-tradecraft/2020/absolute-radiometric-calibration-is-an-essential-tool-to-imagery-science-but-what-is-it.

RD-15. 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-16. Maxar - Imagery Support Data (ISD) Documentation, v 1.1.2, October 2014, Available at: https://dg-cms-uploads-production.s3.amazonaws.com/uploads/document/file/106/ISD_External.pdf

RD-17. Zanoni, "IKONOS Signal-to-Noise Ratio Estimation", March 25-27 2002, JACIE Workshop 2002, Available at: https://ntrs.nasa.gov/api/citations/20040004380/downloads/20040004380.pdf

RD-18. **PROPRIETARY INFO** Satellite Imagery Product Guide, v2.5, 11 June 2020 (Satellite Imagery Product Guide_11062020.pdf), Maxar, Inc.

RD-19. Yalcin, I. et al. (2021) Radiometric Quality Assessment for Maxar HD Imagery. ISPRS, ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 43, 797-804.

RD-20. Keuster, M., Ochoa, T., Jordan, J., Minor, J. (2021). Maxar - RadCalNet as a Source for Outside Validation of Maxar Absolute Radiometric Calibration, RadCalNet User Workshop 2021.

RD-21. Maxar GBDX., (2021) - WorldView-3, Available at: https://gbdxdocs.digitalglobe.com/docs/worldview-3.

RD-22. Viallefont-Robinet, F., Helder, D., Fraisse, R., Newbury, A., van den Bergh, F., Lee, D., Saunier, S., 2018. Comparison of MTF measurements using edge method: towards reference data set. Optics express, 26(26), 33625-33648. doi: 10.1364/OE.26.033625

RD-23. Crespi, Mattia & De Vendictis, Laura. (2009). A Procedure for High Resolution Satellite Imagery Quality Assessment. Sensors (Basel, Switzerland). 9. 3289-313. 10.3390/s90503289. Kohm, K., 2004. Modulation transfer function measurement method and results for the Orbview-3 high resolution imaging satellite. In Proceedings of ISPRS Congress, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXV, part B1, pp. 7-12.

RD-24. Leloglu, U.M., Tunali, E., 2006. On orbit modulation transfer function estimation for Bilsat Imagers. ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., 36(1). https://www.isprs.org/proceedings/XXXVI/part1/Papers/T04-18.pdf

RD-25. Baltsavias, E.P., Pateraki, M., Zhang, L., 2001. Radiometric and geometric evaluation of IKONOS Geo images and their use for 3D building modeling. Joint ISPRS Workshop on High Resolution Mapping from Space 2001, Hannover, Germany, 19–21 September.

RD-26. Kuester, M., Ochoa, T., 2019. Improvements in Calibration, and Validation of the Absolute Radiometric Response of MAXAR Earth-Observing Sensors. Joint Agency Commercial Imagery Evaluation (JACIE) Workshop-2019, Reston, VA, USA, 24 – 26 Sep.

RD-27. Cenci, L., Pampanoni, V., Laneve, G., Santella, C., Boccia, V., (2021). Presenting a Semi-Automatic, Statistically-Based Approach to Assess the Sharpness Level of Optical Images from Natural Targets via the Edge Method. Case Study: The Landsat 8 OLI–L1T Data. *Remote Sensing*, 13, 1593.

RD-28. Breiman, L. (2001). Random forests. Machine Learning, 45(1), 5-32, https://doi.org/10.1023/A:1010933404324.

RD-29. Bouvet, M.; Thome, K.; Berthelot, B.; Bialek, A.; Czapla-Myers, J.; Fox, N.P.; Goryl, P.; Henry, P.; Ma, L.; Marcq, S.; Meygret, A.; Wenny, B.N.; Woolliams, E.R. RadCalNet: A Radiometric Calibration Network for Earth Observing Imagers Operating in the Visible to

Shortwave Infrared Spectral Range. Remote Sens. (2019), 11, 2401, https://doi.org/10.3390/rs11202401

1.2 Glossary

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

BRDF	Bidirectional Reflectance Distribution Function
DSM	Digital Surface model
EDAP	Earthnet Data Assessment Pilot
EO	Earth Observation
ESA	European Space Agency
ESF	Edge Spread Function
EUSI	European Space Imaging
FAIR	Findable, Accessible, Interoperable and Reusable
HD	High Definition
LULC	Land Use Land Cover
MTF	Modulation Transfer Function
NPL	National Physical Laboratory
SNR	Signal-to-Noise Ratio
UAV	Unmanned Aerial Vehicle
WV3	WorldView-3

2. EXECUTIVE SUMMARY

The commercial **WV3** satellite sensor, which is part of the WV constellation owned by **Maxar** (acquired DigitalGlobe), is a Very High-Resolution (**VHR**) optical satellite sensor. It provides the user community with visible, near-infrared and shortwave infrared data, with a spatial resolution of up to 0.30 m.

In recent years, commercial data providers have become very competitive and dynamic, where many of them are now producing products that sufficiently capture the advanced needs of various remote sensing applications, such as those relevant to defence and intelligence, maritime, land resources, etc. In order to achieve the latter, the approach adopted by these commercial data providers is mostly based on two important factors: a constellation of satellites, enabling higher temporal resolutions (i.e. revisit frequency), and increased spatial resolutions. The latter can be achieved by the launch of more sophisticated optical sensors that enable precise and accurate measurements of finer spatial details but this, however, has been demonstrated to not be cost effective due to the technical limits imposed by sensor design and size (e.g. increasing focal length is very expensive).

An alternative, however, is to consider the development and implementation of innovative image post-processing techniques, which are playing an important role in providing high image quality and spatial resolution as a standard service (e.g. BlackSky, SkySat and Pléiades Neo), such as the proprietary '**HD Technology**' developed by Maxar for WV. Maxar provides **visual clarity enhancement imagery** with their HD products, where the HD technology has been applied to the native products, and is described in the HD datasheet [RD-4] as follows: "the HD Technology intelligently increases the number of pixels in an image in such a way that maximises useful information and minimises unnecessary noise and visible pixilation. The technique relies on targeting specific types of information in the source image and using it to discern details that may be obscure or difficult to detect". The HD imagery is resampled to a higher spatial resolution as follows:

- Spatial Resolution WV3 Multispectral Native → HD = 1.20 m → 0.6m
    - Note the multispectral data is resampled to a higher spatial resolution using one of the suitable resampling kernels detailed in [RD-16] and not the resampling kernel provided by the HD technology as it is only applied to the panchromatic data.
- Spatial Resolution WV3 Panchromatic Native → HD = 0.30 m → 0.15 m
- Spatial Resolution WV3 Pansharpened Native → HD = 0.30 m → 0.15 m

It is important to note the above refers to the pixel size and **not** the collective ground sampling distance. Also, classically, any resampling should preserve, at the very least, or improve high spatial frequency content (e.g. increasing the local contrast of an image, reducing noise with smoothing over uniform image regions) in order to allow for a better delineation of objects in the imagery.

This technical note details the data quality assessment of the Maxar WV3 HD 15 cm products and **not** the native products, which have been subjected to comprehensive data quality assessments by the mission provider and the scientific community over the years). A short summary of the results of the EDAP assessments are summarised in the table below, Table 2-1.

Table 2-1: Maxar WorldView-3 HD Assessment Area Results

Assessment Area	Results
Geometric Calibration Quality	**Absolute Geolocation Accuracy** The results of this assessment indicate a high absolute geolocation accuracy of 3.14 m and 1.84 m CE90 for the multispectral and panchromatic bands, respectively. These results are in agreement with the < 4.20 m CE90 minimum requirement specified for orthorectified HD products in [RD-4]. Native-HD Data Quality Comparison: The absolute geolocation accuracy of the HD products is higher than that of the native products, which is expected, and this is most likely due to the higher image measurement accuracy (i.e. ground control pointing). **Band Co-registration Accuracy** The results of this assessment indicate a reasonable band co-registration accuracy for the native bundle multispectral band pairs, which also appears to be maintained by the HD native multispectral band pairs, at < 0.63 m and < 0.61 CE90, respectively. In support of the latter, the error budget is very small – native easting and northing directions of -0.0143 and -0.0248 multispectral pixels, and HD easting and northing of -0.0153 and 0.0032 multispectral pixels. Native-HD Data Quality Comparison: The band co-registration accuracy of the HD products is maintained, when compared to the band co-registration accuracy of the native products, and this is to be expected as this should not be affected by the application of the post-processing HD technology.
Radiometric Calibration Quality	**Absolute Radiometric Accuracy** The absolute radiometric accuracy, using top-of-atmosphere reflectance data from RadCalNet as reference, has been determined and the percentage differences are as follows: Blue 4.04 %, Green 5.14 %, Red 3.95 %, NIR 5.68 % and Pan 5.09 %. Note that this assessment method does not apply any corrections due to surface anisotropy (i.e. directional reflectance). These results are in agreement with the < ±10 % (< 20° off-nadir angle and between 10% and 85% of the dynamic range) for the visible and near-infrared bands minimum requirement specified for the WV satellites in [RD-7]. Native-HD Data Quality Comparison: The absolute radiometric accuracy of the HD products is maintained, when compared to the absolute radiometric accuracy of the native products, and this is expected as this should not be affected by the application of the post-processing HD technology.

Image Quality	**Visual inspections** The results of the visual inspections of the imagery from the sample products procured did not reveal any artefacts or anomalies. Native-HD Data Quality Comparison: This visual inspections of the HD imagery did not reveal any new (i.e. introduced by the post-processing HD technology) artefacts or anomalies when compared to the native imagery. **Modulation transfer Function and Signal-to-Noise Ratio** The results of this assessment, where the values at the Nyquist frequency were assessed, were found consistent in the along-track and across-track directions. However, slight blurring in the across-track direction of the imagery was indicated as well. This image quality metric is particularly important to image interpretability tasks, which is the main use of the HD products. Native-HD Data Quality Comparison: The HD products have lower noise metrics than the native products. However, noise with square patterns and colour deformations were observed in HD products over uniform areas (e.g. desert). **Image Interpretability** The results of this assessment generally indicate an improvement in image interpretability (delineation of objects), via visual clarity, when HD imagery is compared to native imagery (as expected). Native-HD Data Quality Comparison: The image interpretability of HD imagery is improved when compared to that of native imagery. N.B. Maxar recently announced that the latest version of the HD technology, to be released later on this year, will show a significant improvement in performance and quality.

There is no versioning information (e.g. version of processor, version of HD post-processing) given in the products, as confirmed in the product specification, but the sample of products assessed here were generated in October / November 2020 and procured in December 2020. Therefore, any subsequent changes to the products (i.e. processing and / or post-processing updates) will not be represented here.

3. EDAP QUALITY ASSESSMENT

3.1 EDAP Maturity Matrix

Table 3-1: Maxar WorldView-3 HD 15cm Quality Maturity Matrix

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

3.2 Product Information

This section covers a high-level review of product information (including product format, access and availability, and user documentation).

Product Details	
Grade: Good	
Justification: There is information on the platform, the sensor and the sensor products in the documentation disclosed by the data provider [RD-3]–[RD-15] as well as more technical documentation that can be found online (e.g. conference proceedings, peer-reviewed papers, etc.). There is most required and recommended information (e.g. not all versioning information is available), although some is a little hard to find, and so the 'Good' grade has been given.	
Product Name	*WorldView-3 HD 15 cm (procured Map-Ready (LV3D) and Standard View-Ready (OR2A) Bundle (Pan + 4-band) and Pansharpened (4-band))*
Sensor Name	*WorldView-3 (Launched 2014)*
Sensor Type	*Optical (Visible – Shortwave Infrared)*
Mission Type	*Single Satellite (Maxar)*
Mission Orbit	*Sun-synchronous (10:30 AM descending node, 617 km altitude)*
Product Version Number	*The versioning information for generated products is updated according to processing updates (i.e. version of core software) and delivery only. This information can be found in the product metadata. However, the versioning information for additional processing (e.g. HD technology, Pansharpening, etc.) is not provided.*
Product ID	*<catid>_<part>_<band comb (multispectral, pan-chromatic, shortwave-infrared)>_<soli>, where soli is the sales order line item.*
Product Processing Level	*The data provider provides a wide range of products, produced by different processing configurations / levels. However, the product processing level of the sample products procured here are standard view ready and map ready products (equivalent Level 1B and Level 1C).*
Measured Quantity Name	*Digital numbers (DN)* *Linearly scaled top-of-atmosphere spectral radiance*
Measured Quantity Units	*16-bit DN and* $W.st^{-1}.m^{-2}.\mu m^{-1}$
Stated Measurement Quality	*Radiometric Quality: ± 10 % @ < 20° off-Nadir* *Geometric Quality: CE90 < 4.2 m @ < 30° off-Nadir*
Spatial Resolution	• *Very High Resolution* • *Multispectral: 1.24 m GSD (Native 1.24 m, HD 0.6 m Pixel Size) @ Nadir* • *Panchromatic: 0.31m GSD (Native 0.3 m, HD 0.15 m Pixel Size) @ Nadir*

	• Full Swath Width @ Nadir: 13.1 km
Spatial Coverage	*Global (Orbital Inclination 98°)*
Temporal Resolution	*Revisit < 4.5 Days (Latitude Dependent)*
Temporal Coverage	*Mission Lifetime > 7.25 Years*
Point of Contact	*https://www.maxar.com/sales-inquiries*
Product locator (DOI/URL)	*The sensor products are made available upon request only (orders / tasks are placed with the sales imagery support (https://www.maxar.com/sales-inquiries) or through their catalogue (API) of archived imagery ('Discover').*
Conditions for access and use	*Use of this product is subject to the terms and conditions set forth in the applicable Order Quote, the Product Terms and Conditions, available at https://www.maxar.com/legal/product-terms-and-conditions, and / or that license agreement entered into by licensee and Maxar, Inc. or its affiliates.*
Limitations on public access	*No public access.*
Product Abstract	*The product abstract is detailed in [RD-4].*

Availability & Accessibility	
Grade: Good	
Justification: The aforementioned catalogue enables the availability and accessibility of data to meet many of the Findable, Accessible, Interoperable and Reusable *(**FAIR**) Principles. For this reason, the 'Good' grade has been given.*	
Compliant with FAIR principles	*The availability and accessibility of data, especially through their 'Discover' catalogue, meets many of the FAIR principles detailed in [RD-13].*
Data Management Plan	*The data management plan has not been provided by the data provider.*
Availability Status	*The sensor products are made available upon request only (orders / tasks are placed with the sales imagery support (https://www.maxar.com/sales-inquiries) or through their aforementioned catalogue of archived imagery.*

Product Format
Grade: Intermediate
Justification: The general native product format, which has been updated to include format extensions specific to the HD product, is described in [RD-20] and the detailed product format and content is described in [RD-16], which has not been updated to include format and content extensions specific to HD product. *The product format does not demonstrate compliancy to what can be considered as analysis-ready data (there are many interpretations of analysis-ready data, especially by commercial entities, but here we would use the CEOS Analysis Ready Data,*

https://ceos.org/ard/) as it is not an analysis-ready product (Maxar have recently announced the release of their analysis-ready products). *For these reasons, the 'Intermediate' grade has been given.*	
Product File Format	*The product format ensures the following content and metadata files, known as image support data with standard file formats, including:* *•Product Multispectral / Panchromatic / Pansharpened GeoTIFF (.TIFF)* *•Product Image Metadata (.IMD) (or .PVL Parameter Value Language)* *•Product Tile Map (.TIL)* *•Product Readme (.XML)* *•Product Browse Image Icon (.JPG)* *Additional product files are supplied, depending on the product type (e.g. files containing rational polynomial coefficients are included in the product if non-orthorectified, etc.). For more information on the product format, please see [RD-18].*
Metadata Conventions	*None specified.*
Analysis Ready Data?	*The sample products procured are generally not considered as analysis ready data. However, earlier on in the year, Maxar announced the launch of their analysis ready data products which embody the following: 1) atmospheric and radiometric correction, 2) orthorectification and alignment, 3) optimised for cloud computing, 4) configured for localised analysis (metadata and data masks), and 5) accelerated access and direct delivery [RD-6].*

User Documentation	
Grade: Intermediate	
Justification: The information that would typically be found in a user guide can be found spread throughout documentation disclosed by the data provider and / or operator. However, the latter documentation does not contain detail or low-level information on some important aspects of the products and processing, especially algorithm theoretical baseline documentation, due to a number of proprietary constraints (e.g. no information on proprietary HD processing). For these reasons, the 'Intermediate' grade has been given. *Note suggestions for improvement would be to either a) clearly state the issue date of each document, in order for users to determine whether the documentation is being kept up-to-date (if necessary) and if the most recent issue is being used, b) allowing easy and centralised access to all available documentation from the main Maxar website or c) ensure applicability / alignment of the documentation with the product processing software version.*	
User Guide	*[RD-18]* *(QA4ECV standard not applicable)*
ATBD	*Documentation not made available to users. QA4ECV standard not applicable.*

Metrological Traceability Documentation	
Grade: Not Assessable *No documentation of metrological traceability can be found and so the 'Not Assessable' grade has been given.*	
Metrological Traceability Chain / Uncertainty Tree Diagram Available	*Documentation not made available to users.*

3.3 Product Generation

Sensor Calibration and Characterisation – Pre-Flight	
Grade: Basic	
Justification: There is no information available on the radiometric (e.g. linearity, stability, stray light, etc.) and spatial pre-launch calibration and characterisation activities, and only little information on the spectral (e.g. spectral responsivity) pre-launch calibration and characterisation activities, so the 'Basic' grade has been given. *(It is important to note that in the context of this work, where the focus is placed on the aspects of data quality related to HD processing and HD products only, this could be given the 'Not Assessed' grade.)*	
Summary	-
References	-

Sensor Calibration and Characterisation – Post-Launch	
Grade: Intermediate	
Justification: There is only information on the radiometric post-launch calibration and characterisation activities (i.e. information on spatial and spectral post-launch calibration and characterisation activities not provided) of WV3. Despite not all three important aspects of sensor behaviour being covered, the most important aspects are and so the 'Intermediate' grade has been given. *Note the radiometric post-launch calibration and characterisation activities are performed regularly by Maxar, at a level of quality that can be deemed as 'fit for purpose', using appropriate community infrastructure / methods (as detailed below).* *(It is important to note that in the context of this work, where the focus is placed on the aspects of data quality related to HD processing and HD products only, this could be given the 'Not Assessed' grade.)*	
Summary	*The documentation available indicates post-launch calibration and characterisation activities have been performed but only those related to radiometry are described ([RD-10] from 2017 and [RD-4] not dated).* *These activities (i.e. radiometric calibration), which appear to be extensive, include the following:* • *Radiometric calibration using Landsat-8;*

	• *Radiometric calibration using known calibration sites all over the world; and* • *Radiometric calibration using the extensive Maxar calibration range and laboratory located in rural Ft. Lupton (Colorado, U.S.A).* *These activities are described, in detail, in the documents referenced below.*
References	*[RD-4, RD-10, RD-11, RD-13]*

Additional Processing	
Grade: Basic	
Justification: The implementation of orthorectification or pansharpening is an option for all HD products. *HD Technology: The information made available to users is largely focused on the applications of the data produced by the HD technology rather than the HD technology itself, which is to be expected due to the technology being classified as proprietary. Note the product metadata does not include the version of the HD technology used.* *Orthorectification: The information made available to users is largely focused on the definition of orthorectification and the specification of the validated accuracies for the relevant products (native and HD map ready products). There is no information on the resources used (e.g. digital elevation models), etc.* *Pansharpening: The information made available to users is very basic. It appears there are two pansharpening algorithms used for generating pansharpened HD products, the 'LP' and the 'UNB', developed by the University of New Brunswick, algorithms. These are proprietary and so no more information on them is provided.* *For these reasons, the 'Basic' grade has been given.*	
Description and Reference I	*Description: Orthorectification, Reference: -*
Description and Reference II	*Description: HD Algorithm, Reference: -*
Description and Reference III	*Description: Pansharpening, Reference: -*

3.4 Ancillary Information

Product Flags
Grade: Basic
Justification: These products do not contain per-pixel flags (i.e. descriptive quality parameters in product metadata) but they do contain a per-product flag for cloud (i.e. "cloudCover", whose target value is < 3 %, but < 20 % allowed, as a part of Maxar's guarantee for HD products [RD-4]) and a per-product flag for image interpretability. For this reason, the 'Basic' grade has been given.

Product Flag Documentation	*Not applicable as products do not contain flags.*
Comprehensiveness of Flags	*Not applicable as products do not contain flags.*

Ancillary Data	
Grade: Good	
Justification: There is a comprehensive amount of key ancillary information / data, required to define measurement, included in the product metadata if product-specific (e.g. viewing and solar geometry angles, longitude, latitude, altitude) or in the available documentation if non product-specific. However, despite this ancillary information / data being provided also (e.g. cloud cover), uncertainties have not been quantified, where applicable, and so the 'Good' grade has been given.	
Summary	*The descriptions ancillary data, used to interpret measurement, can be found in [RD-4, RD-11, RD-15 RD-17].*
Comprehensiveness of Data	*Not applicable*
Uncertainty Quantified	*Not applicable.*

3.5 Uncertainty Characterisation

Uncertainty Characterisation Method
Grade: Intermediate
Justification: The methods used to characterise uncertainties for important aspects of data quality are detailed but not to a sufficient level where uncertainties are accompanied by a full breakdown of components (including separation into type A and type B uncertainties) and so the 'Intermediate' grade has been given. *(It is important to note that In the context of this work, where the focus is placed on the aspects of data quality related to HD processing and HD products only, this could be given the 'Not Assessed' grade.)*

Summary	*The method(s) used to characterise uncertainties related to the geometric calibration quality of the sensor data is detailed, at a high-level, in [RD-10] and includes "accuracy testing is performed on a regular basis by comparing images to highly accurate ground control points".* *The method(s) used to characterise uncertainties related to the image quality (signal-to-noise ratio, modulation transfer function) are not detailed (or at least not detailed in documentation made available to users).* *The method(s) used to characterise uncertainties related to the radiometric calibration quality of the sensor data is detailed / well documented. These methods, performed as part of their regular calibration / validation campaigns, include cross-comparisons with independent sensors (e.g. Landsat-8).*
Reference	*Geometric uncertainty characterisation method(s): [RD-10]* *Radiometric uncertainty characterisation method(s): [RD-7, RD-10, RD-11, RD-20, RD-26]*

Uncertainty Sources Included	
Grade: Not Assessable	
Justification: The relevant / applicable sources of uncertainties (uncertainties propagated from the auxiliary data used to generate the product, e.g. uncertainties associated with the digital elevation model used, uncertainties associated with ground control points / raster references used) have not been described in the available documentation and so the 'Not Assessable' grade has been given.	
Summary	-
Reference	-

Uncertainty Values Provided	
Grade: Intermediate	
Justification: The uncertainty values provided are per-product and per-mission / per-dataset (i.e. of a given processing level) but the grade 'Intermediate' has been given as they do not cover all important aspects of data quality.	
Summary	*Geometric Uncertainties: The per-product (absolute) geolocation uncertainties are detailed in the product metadata in the forms of two-dimension root mean square error and circular error and per-mission, in terms of minimum requirements / performance. The latter is detailed in the next section. Note other important geometric uncertainties, including those related to band co-registration, have not been detailed.* *Radiometric Uncertainties: The (absolute) radiometric uncertainty is detailed as a single value of ±10 %." [RD-26] for*

	the whole mission. This particular uncertainty value has been derived using native / original WV3 data but it should also apply to WV3 HD data as the radiometric quality of the data should not be impacted by these forms of additional processing.
Reference	*Geometric uncertainties:[RD-4, RD-8, RD-16]* *Radiometric Uncertainties: [RD-26]*

Geolocation Uncertainty	
Grade: Intermediate	
Justification: The geolocation uncertainty values provided per-product and per-mission / per-dataset of a given processing level only demonstrate dependency on several variables, despite the characterisation of these particular uncertainties not being known (aforementioned in the uncertainty characterisation method section), and so for this reason the grade 'intermediate' has been given.	

Summary	*The geolocation uncertainty values provided per-product take the form of a two-dimensional root mean square error (metadata parameter <RMSE2D>) and a circular error (metadata parameter <productAccuracy>, details the worst CE90 in metres for the associated product scale) [RD-16]. The geolocation uncertainty values provided per-mission / per-dataset (e.g. non-orthorectified, orthorectified, HD, etc.) take the form of a circular error.*
	
	Absolute Geolocation Accuracy
	• *Map-Ready (Orthorectified and NMAS Scale 1:12,000)*
	    ○ *30 cm Product: < 4.8 m RMSE [RD-10], < 10.2 m CE90 [RD-4, RD-10]*
	    ○ *15 cm HD Product: RMSE unknown, < 4.2 m CE90 [RD-4]*

Reference	*(See above)*

3.6 Validation

Note this section refers to the validation items related to the independent validation activities conducted by the EDAP team only.

Reference Data Representativeness	
Grade: Good	
Justification: The data provider delivered WV3 native (i.e. reference) and HD product pairs, of seven different sites from six countries (France, Gibraltar, Turkey, Germany, Serbia, Libya), and so the grade 'Good' has been given.	
Summary	*In the context of this assessment, which is to assess the data quality of the HD products generated from the application of the HD technology to the native products, the data provider delivered the native products to be used as reference data. Also, the product pairs (native and HD) delivered by the data provider were of several sites around the world, covering different surface and land cover types (e.g. urban, rural, water).*
Reference	*None.*

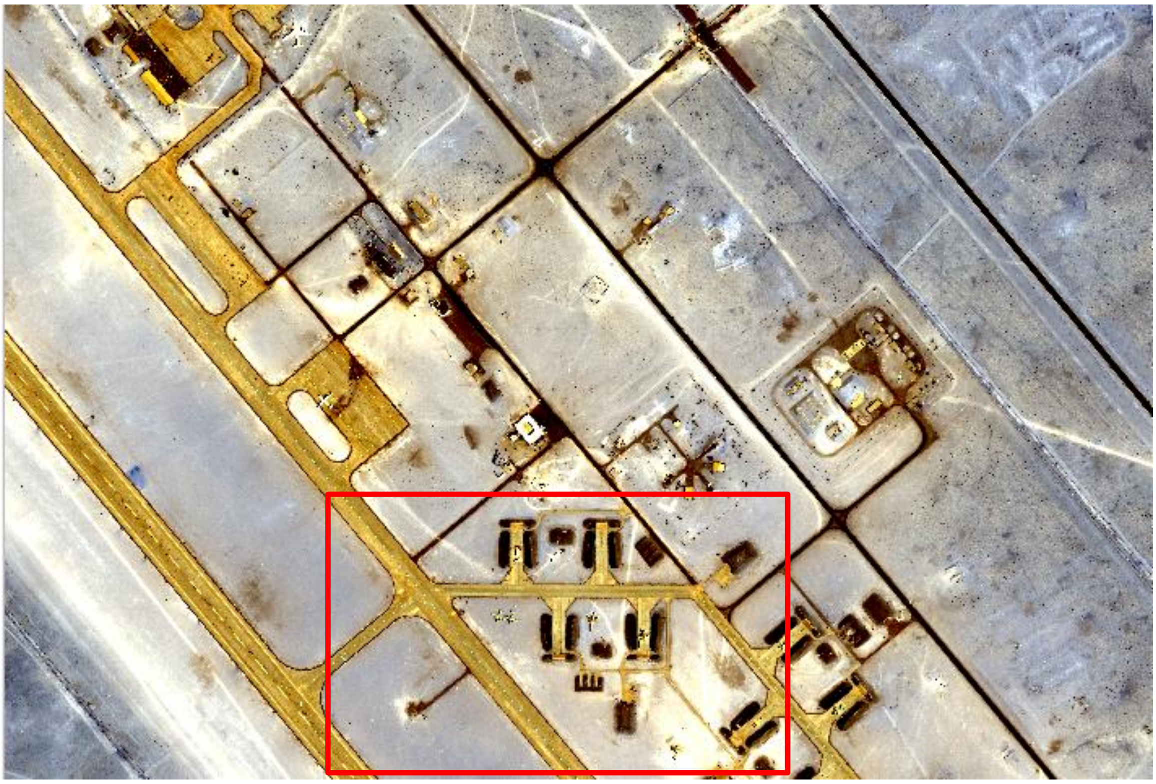
Reference Data Quality & Suitability	
Grade: Good	
Justification: The reference data used by the EDAP optical team comes in various forms (i.e. a variety of regions of interest around the world, a variety of points of interest, reference imagery from suitable reference satellite sensors, etc.), with known uncertainties where applicable, and so for this reason the grade 'Good' has been given.	
Summary	*The primary source of reference data was derived from the native products and the secondary source of reference data, for each assessment area, was derived from the following:* *Geometric Calibration Quality Assessments: The reference data used for these assessments are ground control points, defined by highly accurate Global Navigation Satellite System sensors, for test sites in various locations including La Crau (France) and Ankara (Turkey).* *Radiometric Calibration Quality Assessments: The reference data used for these assessments are derived from relevant / well-established services such as RadCalNet (SI-traceable top-of-atmosphere reflectances).* *Image Quality Assessments: The reference data used for these assessments are derived from specific sites (e.g. image interpretability uses suitable points of interest, and is compared to reference imagery produced by a similar sensor).*
Reference	*[RD-7, RD-19, RD-29]*

Validation Method	
Grade: Intermediate	
Justification: The main validation method used to assess the HD products is based on both qualitative and quantitative, where applicable, comparisons between HD products and their native products. In complement of the latter, validation methods well-documented and used by the scientific community were also sued (these validation methods generally result in the generation of a simple uncertainty (e.g. from statistical distribution of results), also where applicable, and so for these reasons the 'Intermediate' grade has been given.	
Summary	*The validation methods used to assess geometric calibration, radiometric calibration and image quality are all well-documented and used by the scientific community (and are confirmed fit for purpose).*
Reference	*See section 4.*

Validation Results
Grade: Good

Justification: The results of the independent data quality assessments performed here indicate the fundamental data quality of these products is, most importantly, aligned with that of the native products from which they were derived. The data remains well calibrated, both geometrically and radiometrically, and the image interpretability, or "visual clarity", improved with only some smoothing over uniform areas (increase signal-to-noise ratio) being introduced by the HD processing (this is supported by the results of the modulation transfer function and image interpretability assessments). However, this is to be expected as the upscaling of data can be challenging in the first place. *It is important to note the aforementioned improvement in image interpretability should be considered subjective in terms of the users' application.*	
Summary	*The validation results of all assessments are summarised in Section 2 and detailed in Section 4.*
Reference	*Section 2 and 4*

4. DETAILED MAXAR HD 15 CM DATA QUALITY ASSESSMENT



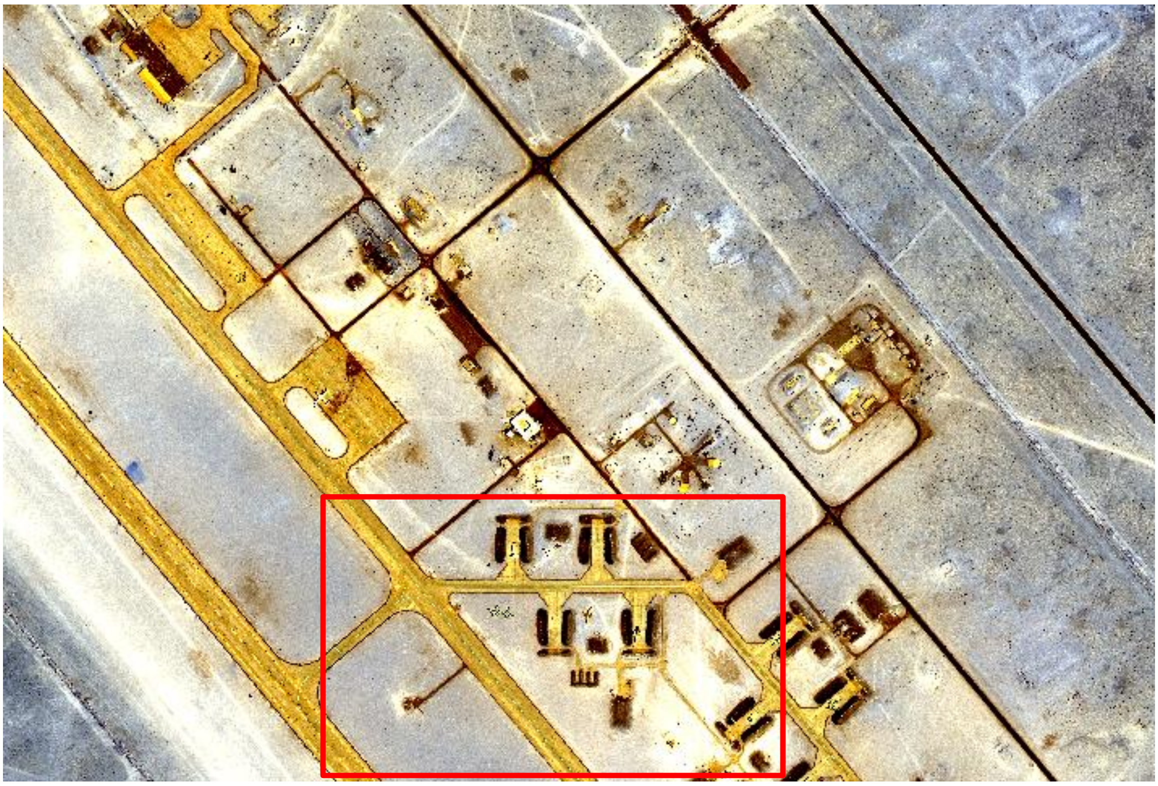


Figure 4-1 Maxar WV3 pansharpened HD (top) and native (bottom) imagery of the Al Jufra Airbase in Libya.

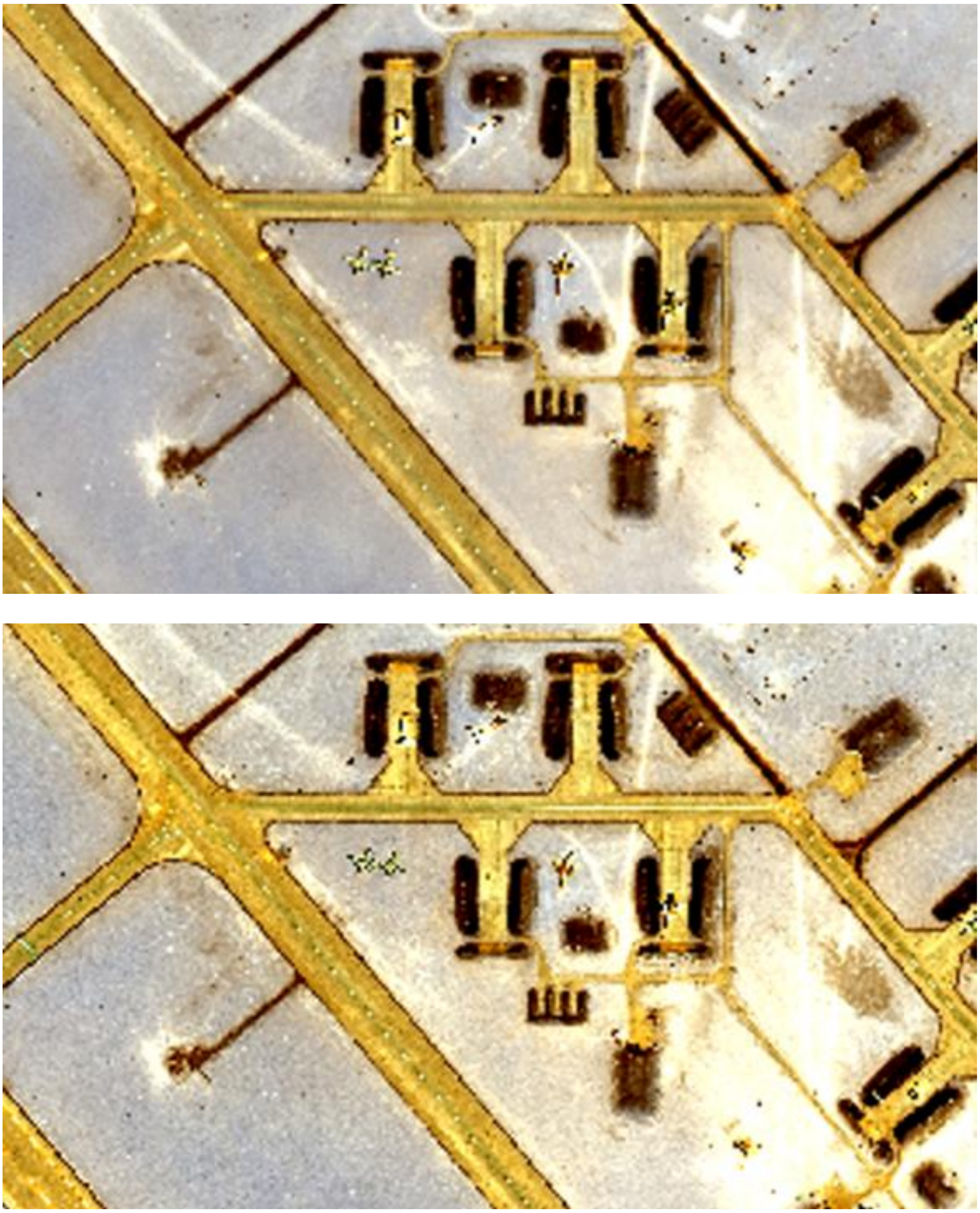


Figure 4-2 This comparison of HD image (top) and native image (bottom) clips from Figure 4-1 generally demonstrate the HD technology's ability to improve the visual clarity of imagery (i.e. edges are better defined / delineated, whilst preserving the radiometry (except for the horizontal road in the middle of the HD clip)).

There are multiple product types, produced by multiple processing chains / configurations (e.g. options relating to orthorectification, pansharpening, resampling, dynamic range adjustment, image data format, tile size, etc.), that can be produced by Maxar for its customers. The product types used for the assessments by the EDAP Optical team are of the following:

1. Standard 2A View-Ready Products (LV2A) HD and Non-HD

These standard view-ready products are georeferenced to a cartographic projection, following *geometric corrections* (spacecraft orbit position and attitude uncertainty, earth rotation and curvature, and panoramic distortion), *radiometric corrections* (relative radiometric response between detectors, non-responsive detector fill, and calibration for absolute radiometry) and *sensor corrections* (internal detector geometry, optical distortion, scan distortion, line-rate variations, (mis) co-registration of multispectral and panchromatic bands) [RD-18].

Note these products are mapped to the average base elevation of the terrain covered by each individual scene from the satellite sensor.

2. Map-Ready (Orthorectified) Products (LV3D) HD and Non-HD

These standard map-ready products, fully processed from view-ready products, contain imagery that has been orthorectified using a *fine* digital elevation model, and are available at a mapping scale of 1:12,000.

The high-level product information on the sample products used are detailed in Table 4-1.

Table 4-1 Maxar WV3 15 cm HD Sample Products

Product No.	Geographic Location	Date	HD?	Pansharpened ?	Processing Level Orthorectified?
1	La Crau (France)	26 08 18 10:54	Yes	No	LV3D
2	La Crau (France)	26 08 18 10:54	No	No	LV3D
3	Al Jufra (Libya)	27 07 20 09:48	No	Yes (UNB	LV2A
4	Al Jufra (Libya)	27 07 20 09:48	Yes	Yes (LP)	LV2A
5	Al Jufra (Libya)	27 07 20 09:48	Yes	No	LV2A
6	Munich (Germany)	19 03 20 10:28	Yes	Yes (LP)	LV2A
7	Munich (Germany)	19 03 20 10:28	No	Yes (UNB)	LV2A
8	Ankara (Turkey)	13 10 20 08:37	Yes	No	LV3D

9	Salon-de-Provence (France)	03 07 17 10:57	Yes	No	LV3D
10	Gibraltar	24 11 19 11:33	Yes	Yes (LP)	LV2A
11	Gibraltar	24 11 19 11:33	No	Yes (UNB)	LV2A
12	Novi Sad (Serbia)	28 08 20 09:48	Yes	Yes (LP)	LV2A
13	Novi Sad (Serbia)	28 08 20 09:48	No	Yes (UNB)	LV2A

Pansharpening UNB = University of New Brunswick, LP = Laplacian Pyramid

Table 4-2 Observation and Solar Geometry Product Metadata

Product No.	M_{OA} (°)	M_A (°)	S_E (°)	S_A (°)	Collected MS, Pan, PS* GSD (m)
1,2	15.0	75.4	55.4	158.8	1.32 MS, 0.33 Pan
3,4,5	2.4	40.1	70.4	116.4	1.32 MS, 0.31 Pan
6,7	18.2	14.8	40.4	162.4	1.32 MS, 0.33 PS
8	21.9	57.9	40.5	161.4	0.36 Pan
9	27.6	179.2	67.4	151.4	1.53 MS, 0.38 Pan
10,11	11.6	291.5	32.9	170.3	1.27 MS, 0.32 PS
12,13	5.9	327.7	52.6	158.0	1.32 MS, 0.31 Pan

Mean off-Nadir view angle (MOA), mean satellite azimuth (MA), mean solar elevation angle (SE), mean solar azimuth (SA) and mean (native) collected GSD (multispectral, panchromatic).

* Note the panchromatic GSD is used for panchromatic and pansharpened products.

4.1 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** and **band co-registration accuracy**.

The imagery, before product production and delivery, are subjected to a number of standard and additional, depending on the processing level, geometric corrections (as detailed in Section 4).

4.1.1 Absolute Geolocation Accuracy

4.1.1.1 Description and Method I

The absolute (planimetric) geolocation accuracy of the orthorectified multispectral and panchromatic imagery is assessed using a method that directly determines the difference between the actual ('absolute') and the apparent location of a set of (independent) ground control points, defined during a field survey using a global navigation satellite system, in the imagery.

The product(s) used to perform this assessment are as follows:

- **Product 1 La Crau HD Non-pansharpened (26/08/18 10:54)**

  This particular site, which is commonly used amongst the optical calibration / validation community, is ideal for determining the orthorectification power of a region of relatively low and homogenous topography. Note the topography of La Crau does not exceed 190 m above the reference ellipsoid.

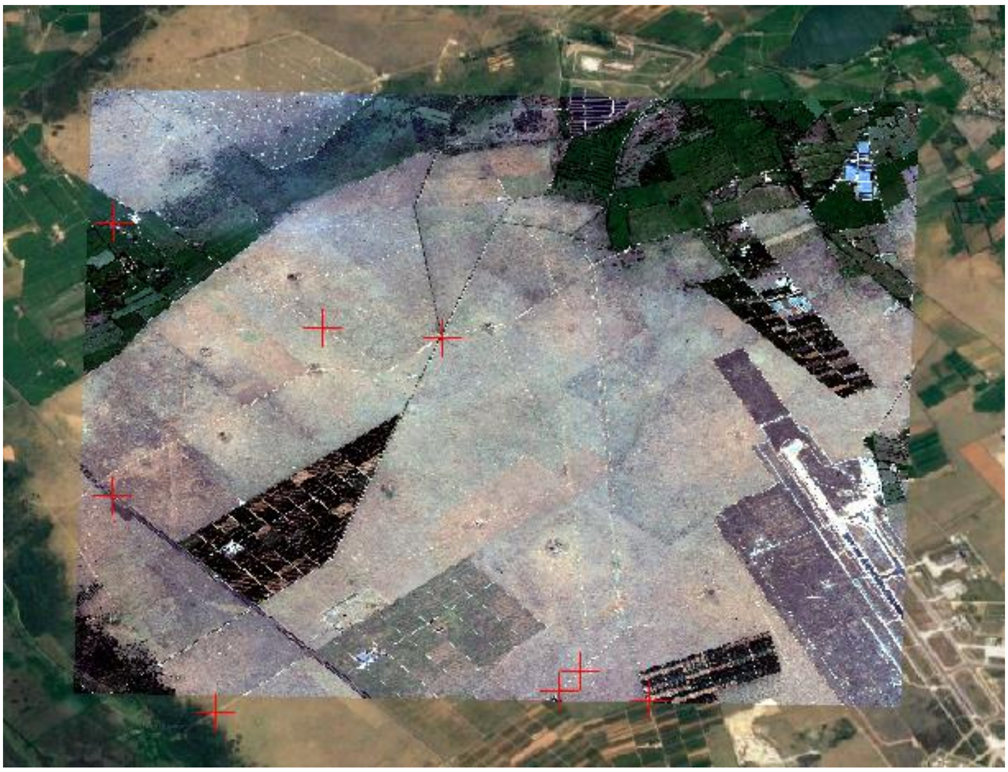


Figure 4-3 The distribution of GCPs used to determine the absolute geolocation accuracy of Product 1.

- **Product 8 Ankara HD Non-pansharpened (13/10/2020 13:08)**

  This particular site was prepared by the Geomatics Engineering group at Hacettepe University (Turkey) for the validation of imagery from very high resolution sensors (including Planet's SkySat constellation).

Figure 4-4 The density and distribution of GCPs used to determine the absolute geolocation accuracy of Product 8.

4.1.1.2 Results

Table 4-3 Maxar WV3 HD: Absolute Geolocation Accuracy Results – La Crau

Parameter	Multispectral (GSD@0.6 m)	Panchromatic (GSD@0.15m)
Viewing Angle (°)	15.1	
GCP Sample #	6[1]	
Mean Easting Error (m)	0.65	0.28
Mean Northing Error (m)	0.66	0.45
Easting Error Standard Deviation (m)	1.47	1.17
Northing Error Standard Deviation (m)	1.85	0.85
Easting Root Mean Square Error (m)	1.61	1.20
Northing Root Mean Square Error (m)	1.97	0.96
Root Mean Square Error (m)	2.54	1.54
Root Mean Square Error (m) Product Metadata	**6.18**	
Circular Error @ 90% (m)	3.14	1.84
Circular Error @ 90% (m) Product Metadata	**10.16**	

[1] *Note one GCP within the scene could not be used as the original feature no longer exists.*

Table 4-4 Maxar WV3 HD: Absolute Geolocation Accuracy Results – Ankara

Parameter	Panchromatic
Viewing Angle (°)	21.9
GCP Sample #	8
Mean Easting Error (m)	-0.81
Mean Northing Error (m)	0.73
Easting Error Standard Deviation (m)	1.06
Northing Error Standard Deviation (m)	0.28
Easting Root Mean Square Error (m)	1.33
Northing Root Mean Square Error (m)	0.78
Root Mean Square Error (m)	1.09
Root Mean Square Error (m) Product Metadata	**6.18**
Circular Error @ 90% (m)	1.81
Circular Error @ 90% (m) Product Metadata	**10.16**

The absolute (planimetric) geolocation accuracy of the orthorectified imagery, as detailed in Table 4-3 and Table 4-4, is relatively good (CE90 multispectral < 5 pixels, panchromatic < 12 pixels) despite a slight degradation due to precision. Also, the absolute (planimetric) geolocation accuracy is well within the minimum requirement specified by the data provider which is **< 4.2 m CE90** [RD-4].

It is interesting to compare the results derived from these assessments with the relevant values provided in the product metadata (ref), shown in Table 4-3 and Table 4-4, but as the product metadata value is lower this then might be the native product or a-priori geolocation (to be confirmed by the data provider).

4.1.2 Band Co-registration Accuracy

4.1.2.1 Description and Method

The multispectral band co-registration accuracies have been determined using an open-source intensity-based image matching tool, which is based on a zero mean normalised cross-correlation algorithm, provided by CNES [RD-14]. The tool is used to match imagery from each pair of bands (e.g. Blue **(band1)** and Green **(band 2)**, Green and Red **(band 3)**, Red and NIR **(band 4)**). Note only the multispectral band pairs have been assessed as non-pansharpened products were used here.

This assessment was performed on the following products:

Product 1 La Crau HD and Non-pansharpened (26/08/18 10:54)

Product 2 La Crau non-HD and Non-pansharpened (26/08/18 10:54)

4.1.2.2 Results

The results of this assessment are detailed in Table 4-5 .

Table 4-5 La Crau: Multispectral Band Co-registration Accuracy (Image Matching Confidence Level @ 95 %). Units: Multispectral Pixels

	Multispectral Native (GSD 1.2 m)				Multispectral HD (GSD 0.6 m)			
	Band Pair: 1_2	**Band Pair: 2_3**	**Band Pair: 3_4**	**Band Pair: 4_1**	**Band Pair: 1_2**	**Band Pair: 2_3**	**Band Pair: 3_4**	**Band Pair: 4_1**
Number of Matched Pixel Total	5502	6095	1125	262	17015	23317	5470	1281
Mean Easting Error (px)	-0.0006	-0.0046	-0.0089	0.0128	0.0003	-0.0105	-0.0145	0.0468
Mean Northing Error (px)	0.0412	-0.0126	-0.0439	0.0394	0.0701	-0.0091	-0.0577	0.0408
Easting Error Standard Deviation (px)	0.0638	0.0632	0.0772	0.1537	0.1498	0.1429	0.1697	0.2780
Northing Error Standard Deviation (px)	0.1025	0.1002	0.1196	0.2993	0.1872	0.1757	0.2185	0.6028
Easting Root Mean Square Error (px)	0.0638	0.0634	0.0778	0.1543	0.1498	0.1433	0.1704	0.2820
Northing Root Mean Square Error (px)	0.1106	0.1010	0.1275	0.3019	0.1999	0.1760	0.2260	0.6043
Root Mean Square Error (px)	**0.1277**	**0.1193**	**0.1493**	**0.3390**	**0.2498**	**0.2270**	**0.2831**	**0.6668**
Circular Error @ 90% Confidence (m / px)	**0.24 /**	**0.22**	**0.28**	**0.63**	**0.24**	**0.21**	**0.27**	**0.61**

In addition to the latter, the error budget has been calculated for each product (as shown in the last six cells of Table 4-5, and is small (i.e. supports good band co-registration accuracies); the error budget rule is that displacement errors are transitive across all band pairs. By summing displacement for each band pair (1, 2), (2, 3) and (3, 4), as shown in the equation below.

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

Where $D_{4,1}$ stands for displacement between the blue band and the NIR band (calculated for the easting and northing direction).

By comparing this estimate $(D_{1,4})$ against the true value $(D_{4,1})$ obtained with image-matching, the error budget of the method is computed (i.e. Error Budget = $D_{B,N}$ + $D_{N,B}$ or $D_{N,B}$ - $D_{B,N}$); the error budget is the following:

- Native Product:
  - Easting Error Budget: 0.0013 MS Pixels
  - Northing Error Budget: 0.0547 MS Pixels
- HD Product
  - Easting Error Budget: 0.0715 HD MS Pixels
  - Northing Error Budget: 0.0375 HD MS Pixels

4.2 Radiometric Calibration Quality

The radiometric calibration quality assessments have been performed here at a coarse level as the radiometric calibration quality of the data has already been assessed by the operator and the scientific community in detail. It is also important to note the radiometry should not be impacted by processing level or additional processing (e.g. HD processing) and so we expect the radiometric quality of the native products to be preserved by the HD products.

The radiometric calibration, or correction, of sensor data sees to the successful conversion of raw data (i.e. digital numbers) to top of atmosphere spectral radiance or reflectance, using coefficients (e.g. bias, gain, solar spectral irradiance constants) derived pre-flight in laboratory conditions. This is important as it improves the interpretability and quality of the sensor data (and is particularly important when comparing multiple sensor datasets over a period of time, which is commonly performed by the scientific community).

The digital number (DN) to top-of-atmosphere spectral radiance (L_b) conversion of sensor data, per band (b, see Table 4-6 for characteristics and Figure 4-5 for relative spectral response) is enabled by the following (indicated specifically for Maxar products):

$$\boldsymbol{L_b = DN_b * Gain_b + \frac{AbsCalFactor}{EffectiveBandwidth} + Bias_b}$$

Where:
Gain and *Bias* values are delivered in [RD-4] are parameters that *AbsCalFactor* and *EffectiveBandwidth* values are delivered in the product metadata file.

The top-of-atmosphere spectral radiance (L_b) to reflectance (ρ_b), per band (b), is enabled by the following:

$$\boldsymbol{\rho_b = \frac{\pi * L_b * d^2}{E_{0b} * Cos(\theta_s)} = \frac{Radiation\ (radiation\ leaving\ the\ Earth)}{Irradiance\ (Radiation\ reaching\ the\ earth\ from\ the\ Sun)}}$$

Where:
E_{0b} is solar spectral irradiance at the sensor for band b (units: Wm^{-2}μm^{-1}).
θ_s is solar zenith angle at the tome / location of acquisition (units: degrees).
d^2 is Sun-Earth distance at the time of acquisition (units: astronomical units).

(All coefficients mentioned above can be found in the product user guide, the product metadata and online.)

Table 4-6: Spectral Bands

Band	Effective Bandwidth λ (nm)	Centre Wavelength λ (nm)
Panchromatic	450 - 650	649.4
Blue	445 - 517	481.9
Green	507 - 586	547.1
Red	626 - 696	660.1
NIR1	765 - 899	835

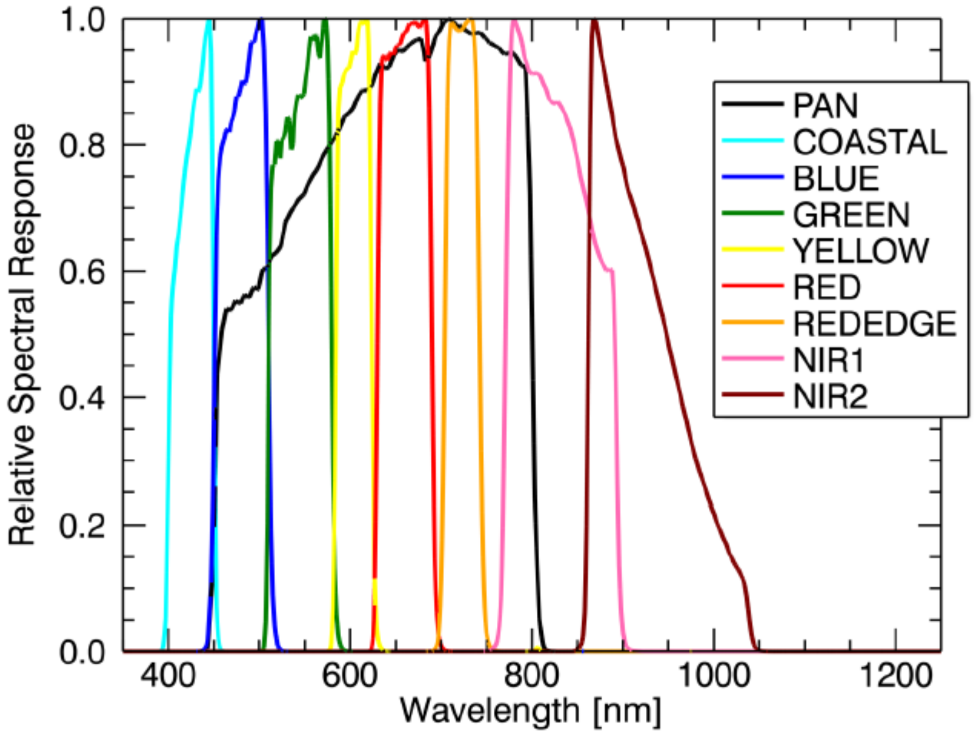


Figure 4-5: WorldView-3 Relative Spectral Response (nm) for the VNIR bands [RD-11].

The determined absolute radiometric calibration accuracy will be evaluated against the minimum requirement, which is specified as **± 10 % (< 20° off-nadir angle and between 10 and 85 % of the dynamic range (outside of this dynamic range there is no specification))** [RD-14, RD-26].

4.2.1 Absolute Radiometric Accuracy

4.2.1.1 Description and Method

The method used to determine the absolute radiometric calibration accuracy of the sensor's bands is based on comparing the top-of-atmosphere reflectance values derived from the sensors acquisitions of the chosen RadCalNet calibration sites with the top-of-atmosphere reflectance values derived from the RadCalNet calibration sites themselves (i.e. reference top-of-atmosphere reflectance values).

The RadCalNet calibration sites, operated by the CEOS Working Group for Calibration and Validation (WGCV) Infrared and Visible Optical Sensors (IVOS), provides the scientific community with the following:

- Top-of-atmosphere reflectance values, derived from both in-situ surface and atmosphere measurements (e.g. surface pressure, columnar water vapour, columnar ozone, aerosol optical depth, etc.) that are SI-traceable, at:
- 30-minute intervals between 09:00 and 15:00 local standard time (cloud-free data only), and 10 nm spectral sample intervals between 400 nm and 1000 nm.

Note the RadCalNet top-of-atmosphere reflectance values are representative of nadir viewing observations only, so comparison to sensor top-of-atmosphere reflectance values should be used with caution - when the sensor viewing zenith angle deviates significantly from nadir, both atmospheric and surface non-Lambertian behaviour can lead to significant deviation from at-nadir simulated signal. The correction for the latter (i.e. off-nadir viewing angle effects), as well as illumination (solar) angle effects, can be done using bi-directional reflectance modelling.

The product(s) used to perform this assessment are as follows:

Product 1 La Crau HD Non-pansharpened (26/08/18 10:54:04)

Table 4-7 : RadCalNet La Crau Calibration Site Description

Parameter	Description
Geographic Location	Latitude: 43.558889, Longitude: 4.864167, Altitude: 20 m
Characteristics	The RadCalNet top-of-atmosphere reflectance spectra are representative of a disk of 30 m radius.

Figure 4-6 The La Crau RadCalNet site located in Product 1.

4.2.1.2 Results

The results of this assessment can be found in Table 4-9.

Table 4-8 Maxar WV3 Sensor Observation Conditions (Solar and Viewing Geometries)

Product	Sensor Viewing Angle (°)	Sensor Azimuth Angle (°)	Solar Elevation Angle (°)	Solar Azimuth Angle (°)	Water Vapour (g/cm)	AOD ()
1	15.0	75.4	55.4	158.8	0.53	0.076

The primary estimate of the absolute radiometric accuracy, without the implementation of **bidirectional reflectance distribution function** (**BRDF**) corrections (which is generally needed when the off-nadir viewing angle is relatively large (as is the case here, see Table 4-8)), is generally within the minimum requirement specified for these bands and therefore confirms the radiometric quality of the data has been preserved. It is relevant to note that the absolute radiometric calibration of all Maxar satellites is performed regularly using acquisitions with < 20° off-nadir viewing angle and reflectance data from RadCalNet, and the results of those acquisitions with the larger off-nadir viewing angles indicate absolute radiometric accuracies < 10 % (as it takes into account significant variations due to surface BRDF and longer atmospheric paths) [RD-25].

Table 4-9 La Crau: Maxar WV3 and Simulated Maxar WV3 (RadCalNet) TOA Reflectances

		ρ TOA Reflectance				
Product	**Origin**	**Blue**	**Green**	**Red**	**NIR**	**PAN**
1	RadCalNet	0.136102	0.141313	0.168314	0.280851	0.181063
	Sensor	0.130598	0.134053	0.161673	0.264903	0.168225
	Difference (%)	4.043645	5.137491	3.945364	5.678442	7.090289

The difference, expressed as a percentage, between sensor top-of-atmosphere reflectances ($\boldsymbol{\rho_b}\, work$) and simulated sensor top-of-atmosphere reflectances ($\boldsymbol{\rho_b}\, simulated$), using RadCalNet data, is calculated as follows:

$$\rho_b = ((\boldsymbol{\rho\_b}\ simulated - \boldsymbol{\rho\_b}\ work)/(\boldsymbol{\rho\_b}\ simulated)) * 100$$

The secondary estimate of absolute radiometric accuracy, with the implementation of BRDF corrections (very) coarsely determined from a BRDF model developed for another but similar sensor, are given in Table 4-10. Note more accurate BRDF corrections could not be obtained, or was not suitable, from the traditional sources (e.g. MODIS Albedo / BRDF products).

Table 4-10 La Crau: Coarse BRDF-corrected Maxar WV3 and Simulated WV3 (RadCalNet) TOA Reflectances

		ρ TOA Reflectance				
Product	**Origin**	**Blue**	**Green**	**Red**	**NIR**	**PAN**
1	RadCalNet	0.136102	0.141313	0.168314	0.280851	-
	Sensor	0.135982	0.145631	0.171579	0.273158	-
	Difference (%)	0.088125	-3.055611	-1.939958	2.739173	-

4.2.2 Temporal Radiometric Accuracy

This assessment could not be performed as the appropriate products (i.e. multiple acquisitions over a given pseudo-invariant calibration site) have not been procured from the data provider.

4.3 Image Quality

This section describes the assessment of product image quality on the procured products in terms of the **Modulation Transfer Function** (**MTF**) and **Signal-to-Noise Ratio** (**SNR**), and the **Maxar HD Technology.**

4.3.1 Modulation Transfer Function and Signal-to-Noise Ratio

The MTF is an important image quality metric, which has a complex relationship with other image quality metrics importantly including the GSD and the SNR, that is commonly used to characterise (quantify) image sharpness. The products used to assess MTF and SNR are of the following:

- **Product 9 Salon-de-Provence HD (03/07/17 10:57)**

4.3.1.1 Method and Description

The MTF was estimated using the classical slanted-edge (i.e. knife-edge) method described in [RD-21], which is defined by the following four main steps:

(1) Target edge identification and orientation;
(2) Target edge modelling;
(3) Computation of the Edge Spread Function (**ESF**);
(4) Computation of the MTF from the ESF.

The ESF modelling is a crucial processing step and the methods used can be divided into two main categories: modelling based on a parametric or on a non-parametric approach. The two approaches have been systematically tested and, in most cases, the parametric approach is usually chosen [RD-22] since it has many advantages and only the disadvantage of losing fidelity in the modelling of the system. However, in the context of assessing the Maxar HD products, it was possible to use the non-parametric approach; even if this approach is less robust to noise, it was more convenient to assess deformation originating from the HD processing.

This assessment typically makes use of suitable and separable artificial targets (e.g. checkboard) and natural targets (containing suitable image edges and sharp transitions). The assessment of this data has made use of the artificial target located in Salon-de-Provence (France). Although preliminary assessments were carried out with a selection of natural targets (RD-19), the results were not yet conclusive due to the inadequacy of such targets.

4.3.1.2 Results

The MTF, SNR, RER and FWHM results obtained from the MTF target in Salon-de-Provence, shown in Figure 4-7, are detailed in Table 4-11.

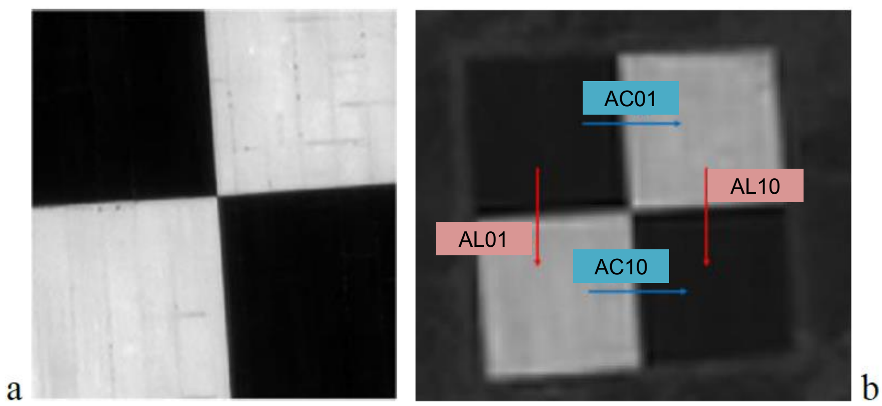


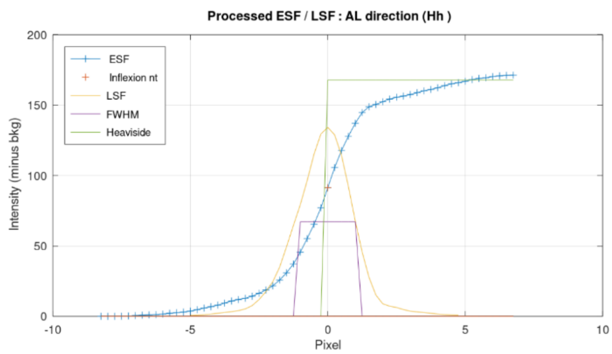
Figure 4-7 15 cm Panchromatic HD (a) artificial MTF target in Salon-de-Provence, 15 cm Pansharpened HD, and (b) the four directions (AL01, AL10, AC01, AC10) of the MTF calculation (Red band).

Table 4-11: SNR, RER, and FWHM results obtained from the MTF of targets in HD non-pansharpened and pansharpened imagery.

Target	Direction	SNR	RER	FWHM	MTF
MTF target in Salon de Provence (HD Non-PS)	AL01 (AL)	25.79	11.42	2.25 pixel	0.04
	AL10 (AL)	15.24	-11.03	2.75 pixel	0.02
	AC01 (AC)	10.84	13.88	2.25 pixel	0.06
	AC10 (AC)	6.66	-12.85	2.00 pixel	0.06

The assessments were performed multiple times using the artificial target, at different lines, in order to obtain calculations for edges without colour deformations (i.e. the paint used to define the target is clearly cracked, as shown in Figure 4-7a, and repainting is foreseen). These calculations included the FWHM, SNR, RER and MTF, for all four directions (i.e. two along-track (AL) and two across-track (AC) as shown in Figure 4-7), which are detailed in Table 4-11 and Figure 4-8 - Figure 4-11.

According to [RD-27], the FWHM provides a more robust estimation of sharpness than MTF for a given spatial resolution. In addition, the FWHM values ranging between 1-2 indicates images with suitable sharpness, whereas values above 2 indicates images with blur effects. Considering the FWHM results in Table 4-11, it can be said that the images are slightly blurred especially in the AL direction. The MTF values were evaluated at the Nyquist frequency, and found consistent in the AC directions. The RER is the slope of the ESF and the SNR is the ratio of the edge height to the mean standard deviations on either side of the ESF curve [RD-22]. The results obtained here are again consistent in both AL and AC directions, although again indicate blurring effect by the ESF and RER values.



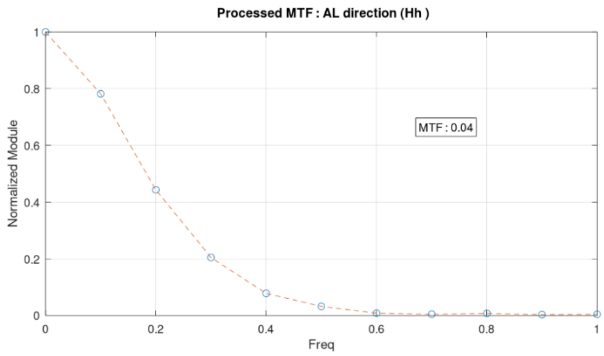
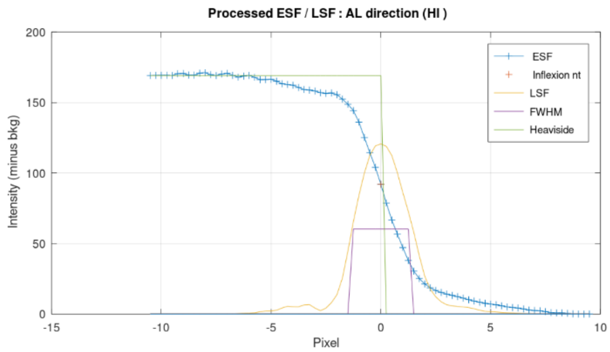


Figure 4-8. The ESF, LSF, FWHM, SNR, RER and MTF results over the AL01 direction (along-track) from the panchromatic band in Salon-de-Provence.



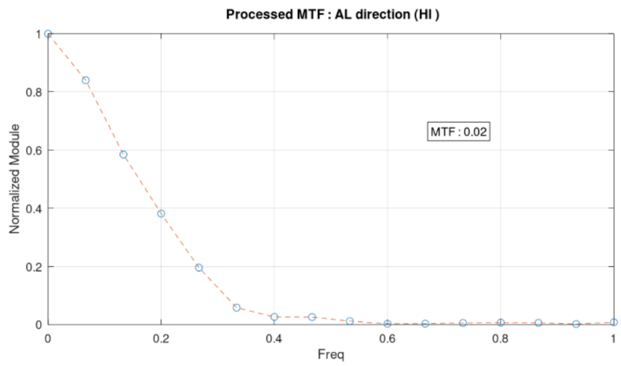
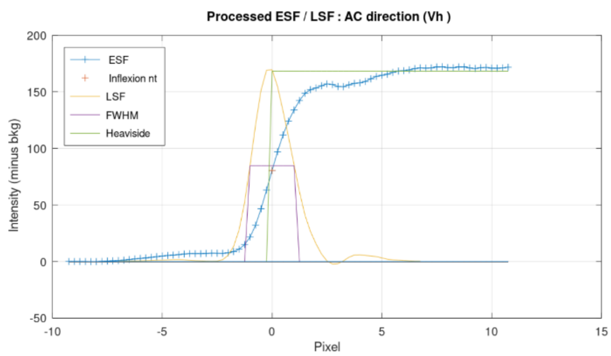


Figure 4-9 The ESF, LSF, FWHM, SNR, RER and MTF results over the AL10 direction (along-track) from the panchromatic band in Salon-de-Provence.



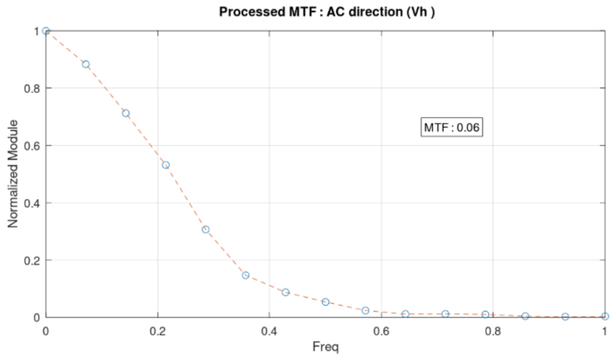
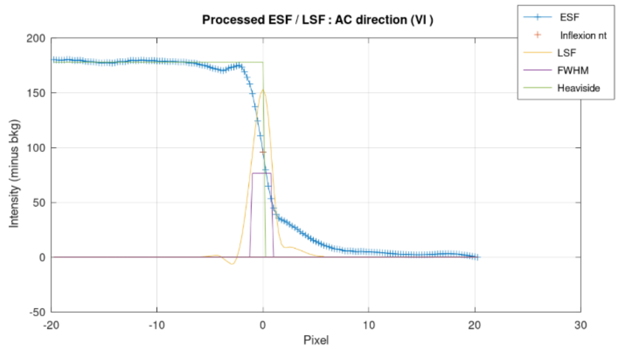


Figure 4-10 The ESF, LSF, FWHM, SNR, RER and MTF results over the AC01 direction (across-track) from the panchromatic band in Salon-de-Provence.



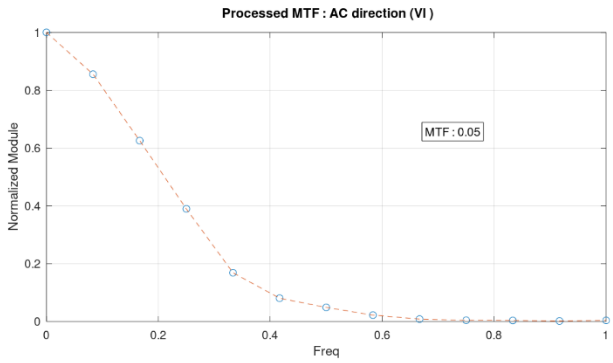


Figure 4-11 The ESF, LSF, FWHM, SNR, RER and MTF results over the AC10 direction (across-track) from the panchromatic band in Salon-de-Provence.

4.3.2 Image interpretability

This assessment is performed in order to determine if the image quality has been preserved or improved, where applicable, despite higher level processing / application of the HD technology.

The products used for this assessment are the following:

- **Product 1 and 2 La Crau (France) Native and HD Non-Pansharpened**
- **Product 3, 4, 5 Al Jufra (Libya) Native and HD Pansharpened**
- **Product 6 Munich (Germany) Native and HD Pansharpened**

- **Product 7 Ankara (Turkey) UAV and HD Non-Pansharpened**
- **Product 8 Novi Sad (Serbia) Native and HD Pansharpened**

4.3.2.1 Description and Method I

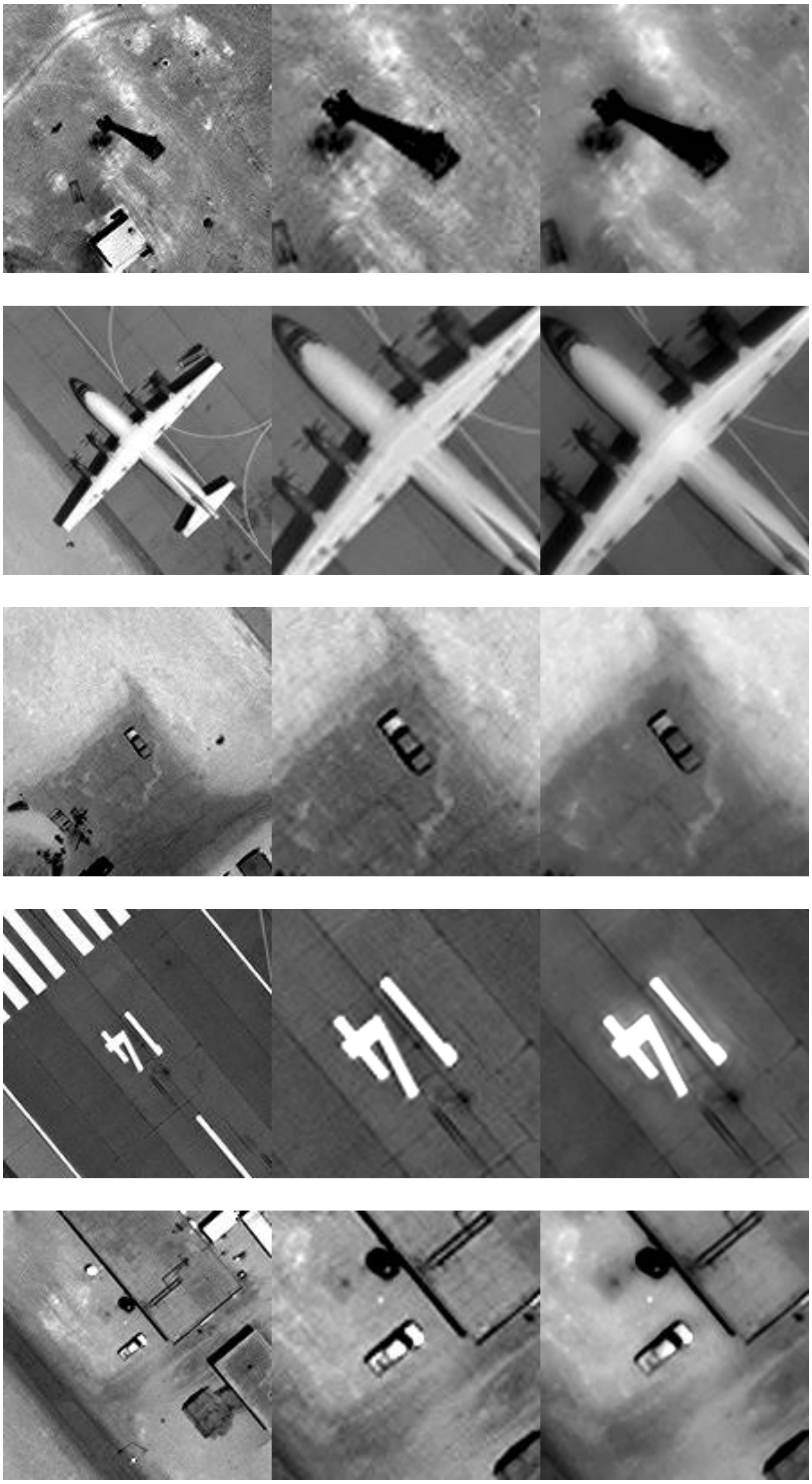
This method assesses changes to image interpretability (expected to improve) by making comparisons between clips of selected points of interest (artificial or natural) from native, pseudo-HD[2] and HD imagery.

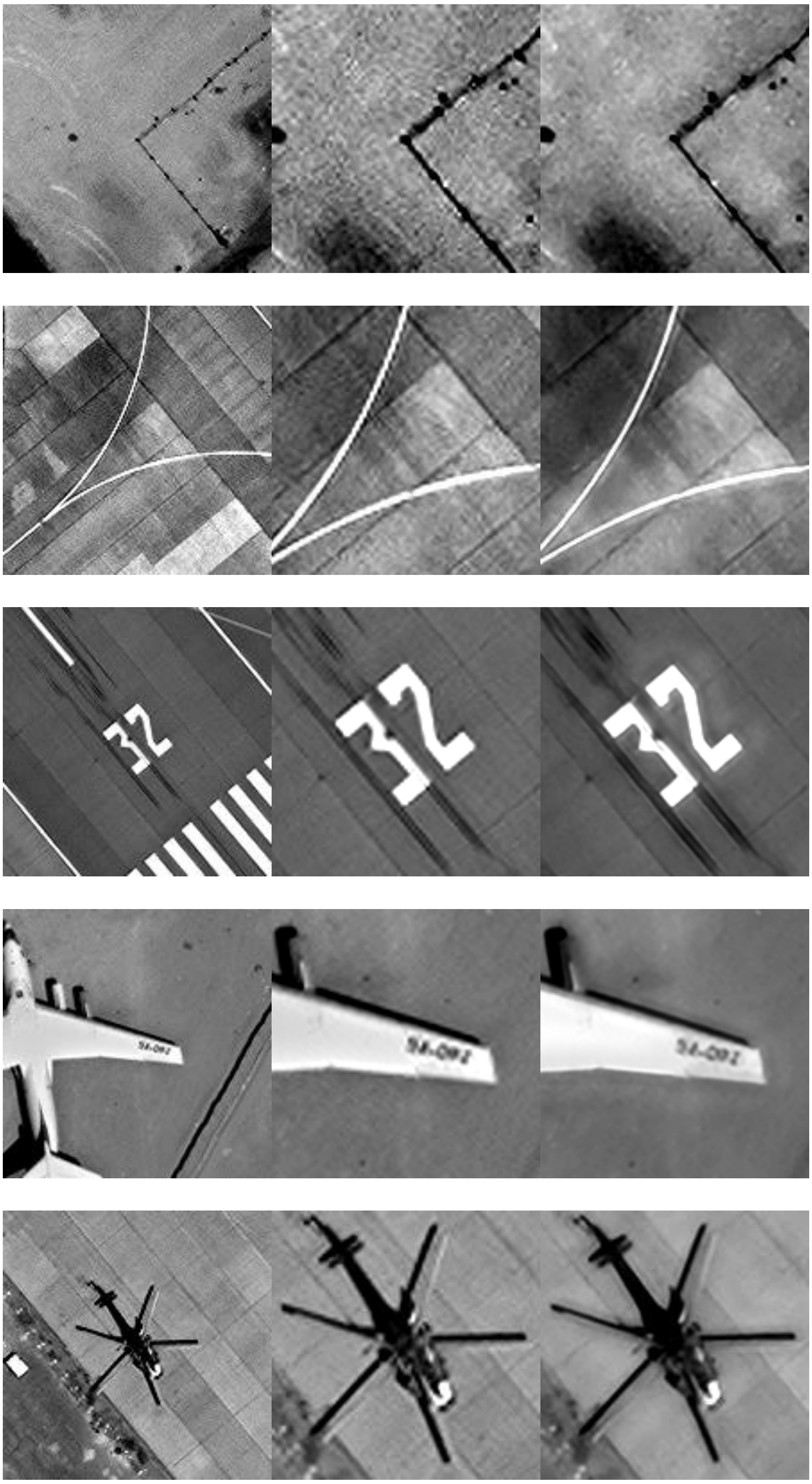
The characteristics of the points of interest (**POI**) assessed in imagery of the airbase in Al Jufra are detailed in Table 4-12.

Table 4-12 Image Interpretability: Al Jufra POI

ID	POI Description	POI Location
1	Airplane 1	(596162.49702095543034375 3232005.1809273287653923
2	Pylon	(601380.20861889945808798 3229782.62166018458083272)
3	Airplane 2	(597378.01717768737580627 3230872.48016842780634761)
4	Car 1	(598077.23673160478938371 3230226.62316705612465739)
5	Runway Marking 1	(596133.93552051356527954 3231761.42329424992203712)
6	Car 2	(596498.25133649352937937 3232831.9871211526915431)
7	Fence	(597903.49506512505467981 3231168.30210403632372618)
8	Runway Marking 2	(597526.51011963852215558 3230518.32651639636605978)
9	Runway Marking 3	(598499.39182434091344476 3228923.53828483074903488)
10	Airplane Wing Marking	(597347.61235904751811177 3231521.53328682854771614)
11	Helicopter	(597099.51230348588433117 3231493.50899329222738743)
12	Airplane 3	(599117.17976493120659143 3228843.85259394347667694)

[2] *Pseudo-HD = native imagery simply resampled to a higher spatial resolution using a gdal cubic resampling kernel.*




32

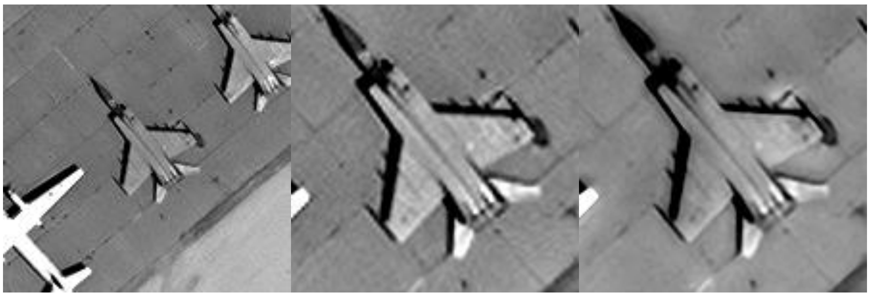


Figure 4-12 Libya – Al Jufra Airport POIs: Band 4 (left) Pansharpened (30 cm), (middle) Pansharpened pseudo-HD (15 cm) and (right) Pansharpened HD (15 cm).

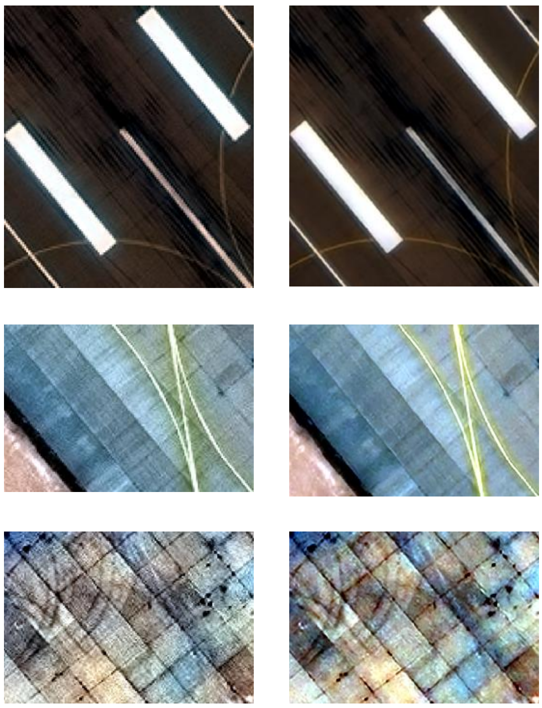
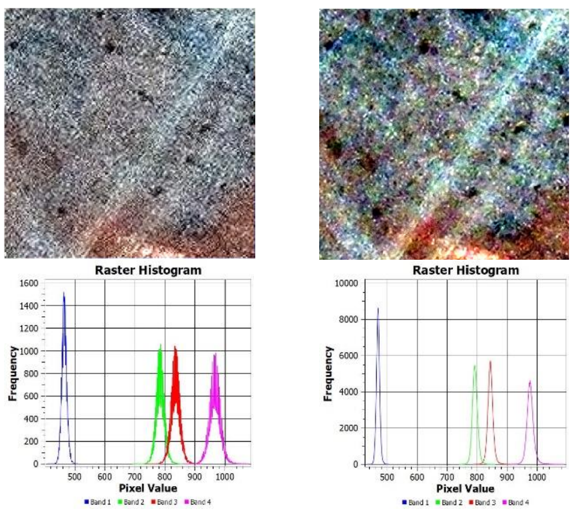
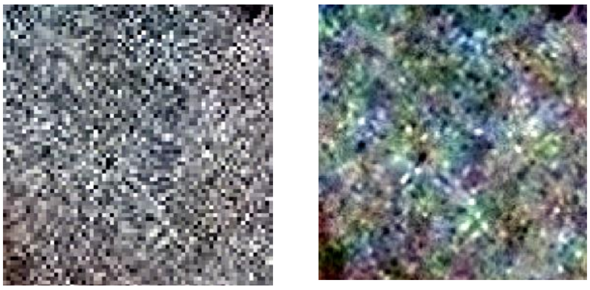
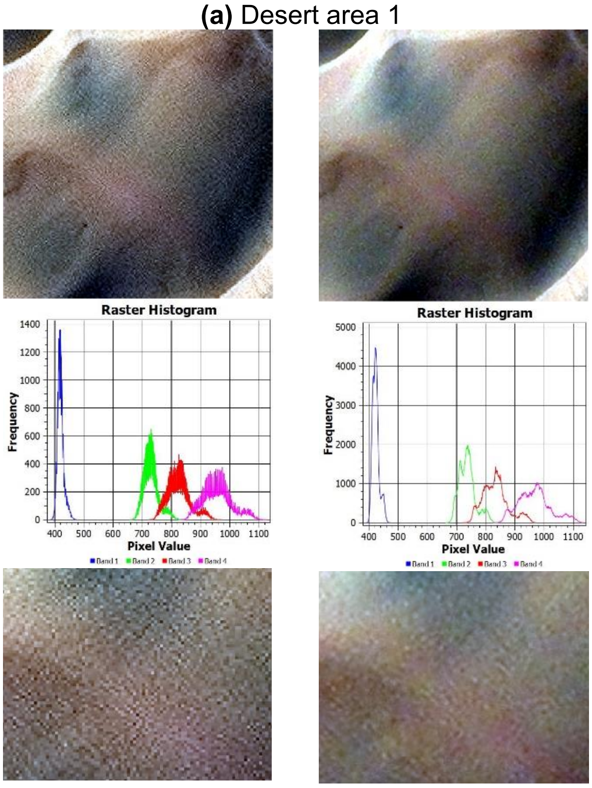


Figure 4-13 Libya – Al Jufra Airport POIs: RGB Pansharpened Original 30 cm (left) and Pansharpened HD 15 cm (right) image.





(a) Desert area 1



(b) Desert area 2

Figure 4-14: Libya – Desert POIs: RGB Pansharpened Original 30 cm (left) and Pansharpened HD 15 cm (right) image.

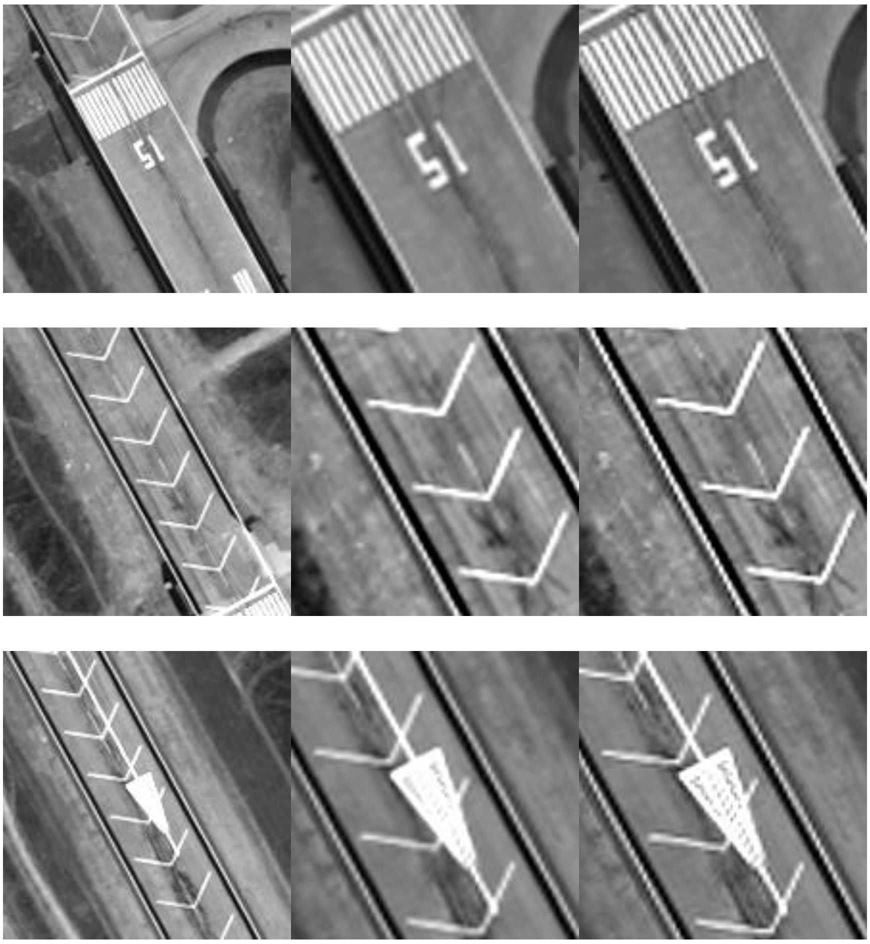
The results of this particular comparison indicate that whilst the overall visual clarity is improved, as expected, there is evidence of blurring and oversmoothing being introduced. However, the cause of the latter cannot be clearly isolated as these products were not pansharpened using the same pansharpening algorithm (i.e. products using the same pansharpening algorithm would be needed in order to determine whether the blurring and oversmoothing was caused by the application of the HD technology). The results of the desert site (i.e. uniform area) comparison show evidence of the latter, along with colour deformation and noise (square patterns). Note the original products contain evidence of aliasing.

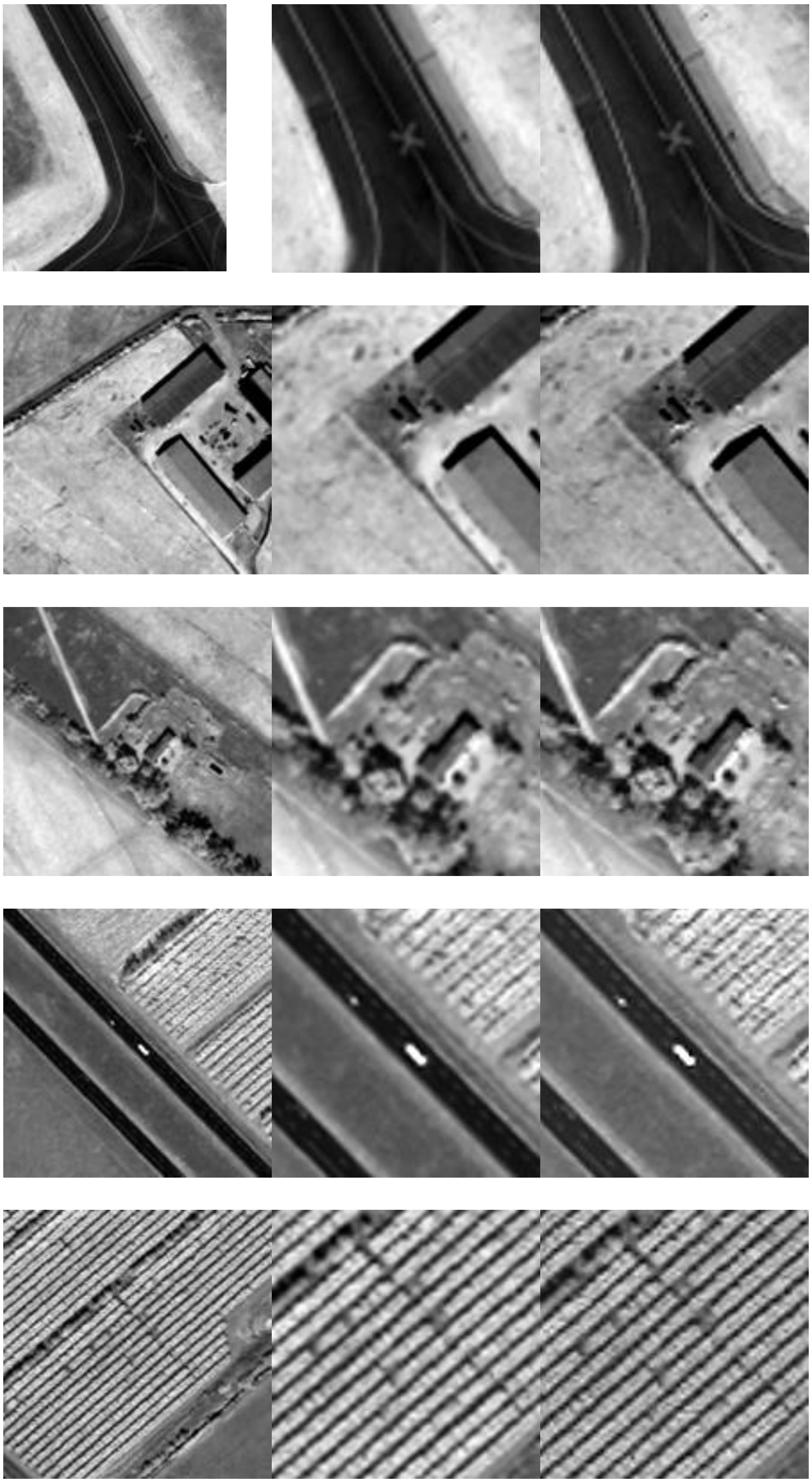
4.3.2.2 Results II

The characteristics of the points of interest assessed in imagery of La Crau are detailed in Table 4-13.

Table 4-13 Image Interpretability: La Crau POI

ID	POI Description	POI Location
1	Runway Marking 1	(654610.34543999785091728 4822266.77333124820142984)
2	Runway Marking 2	(654526.97541363909840584 4822395.6701546860858798)
3	Runway Marking 3	(654139.81937475502490997 4823141.34200909268110991)
4	Runway Marking 4	(655273.44263149693142623 4821678.83708853181451559)
5	Car 1	(646917.98554172751028091 4826606.70310482569038868)
6	Car 2	(646849.07994384656194597 4826397.63388695009052753)
7	Motorway	(647637.33147425577044487 4821695.27094998396933079)
8	Crop Lines	(648430.22864769329316914 4821072.37056614086031914)
9	Solar Panels	(654590.16989557852502912 4827540.42109812889248133)





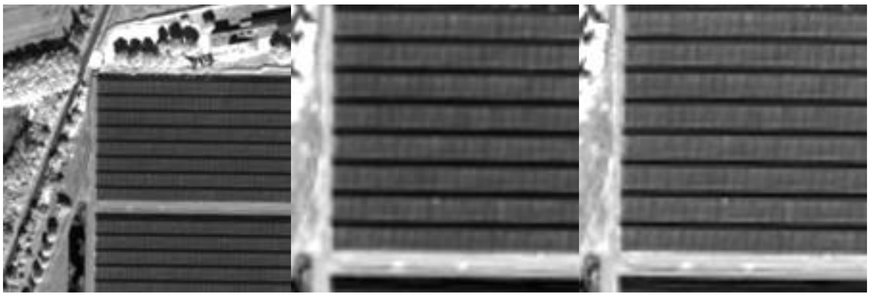
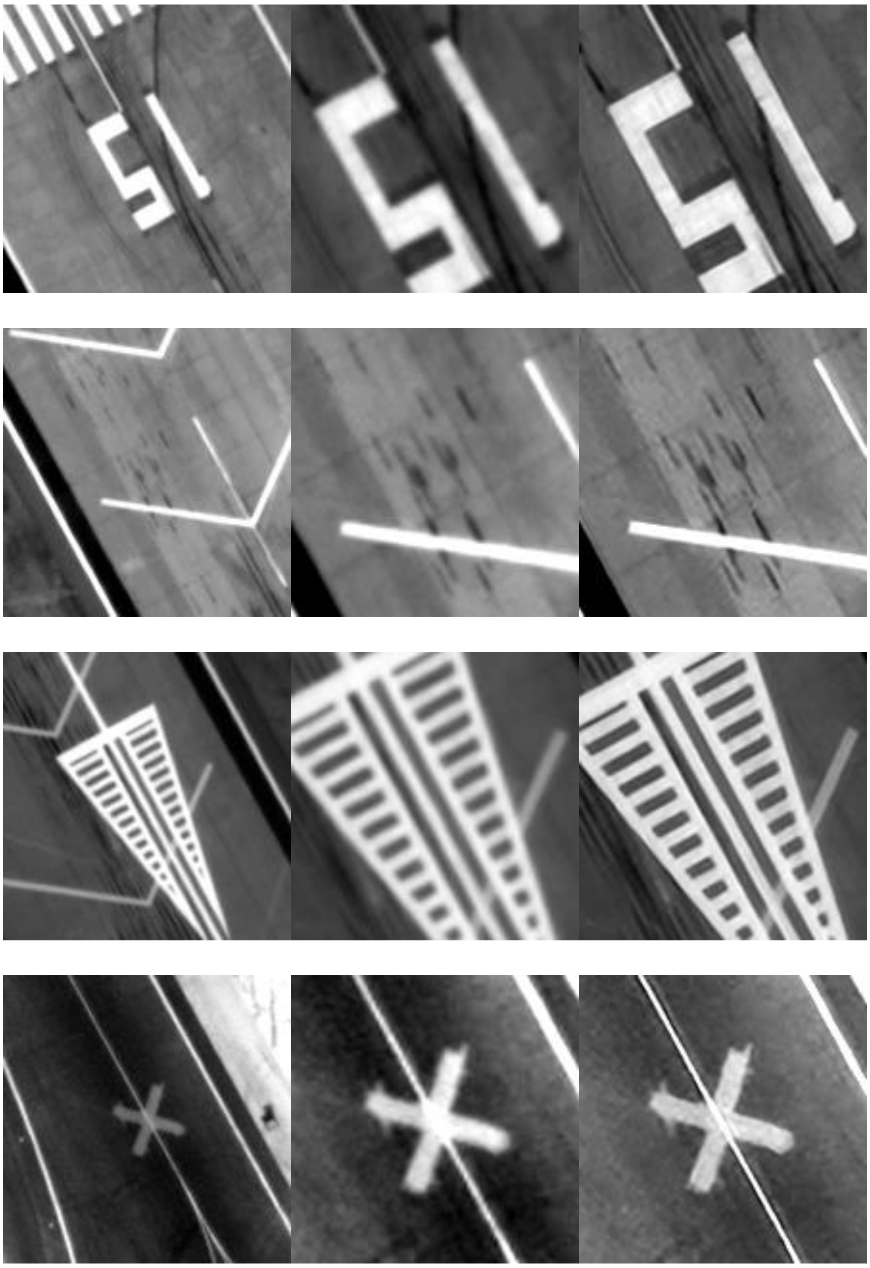


Figure 4-15 France - La Crau POIs: Multispectral (left) Band 4 Original (1.2 m), (middle) Band 4 Pseudo-HD (0.6 m) and (right) Band 4 HD (0.6 m) imagery.



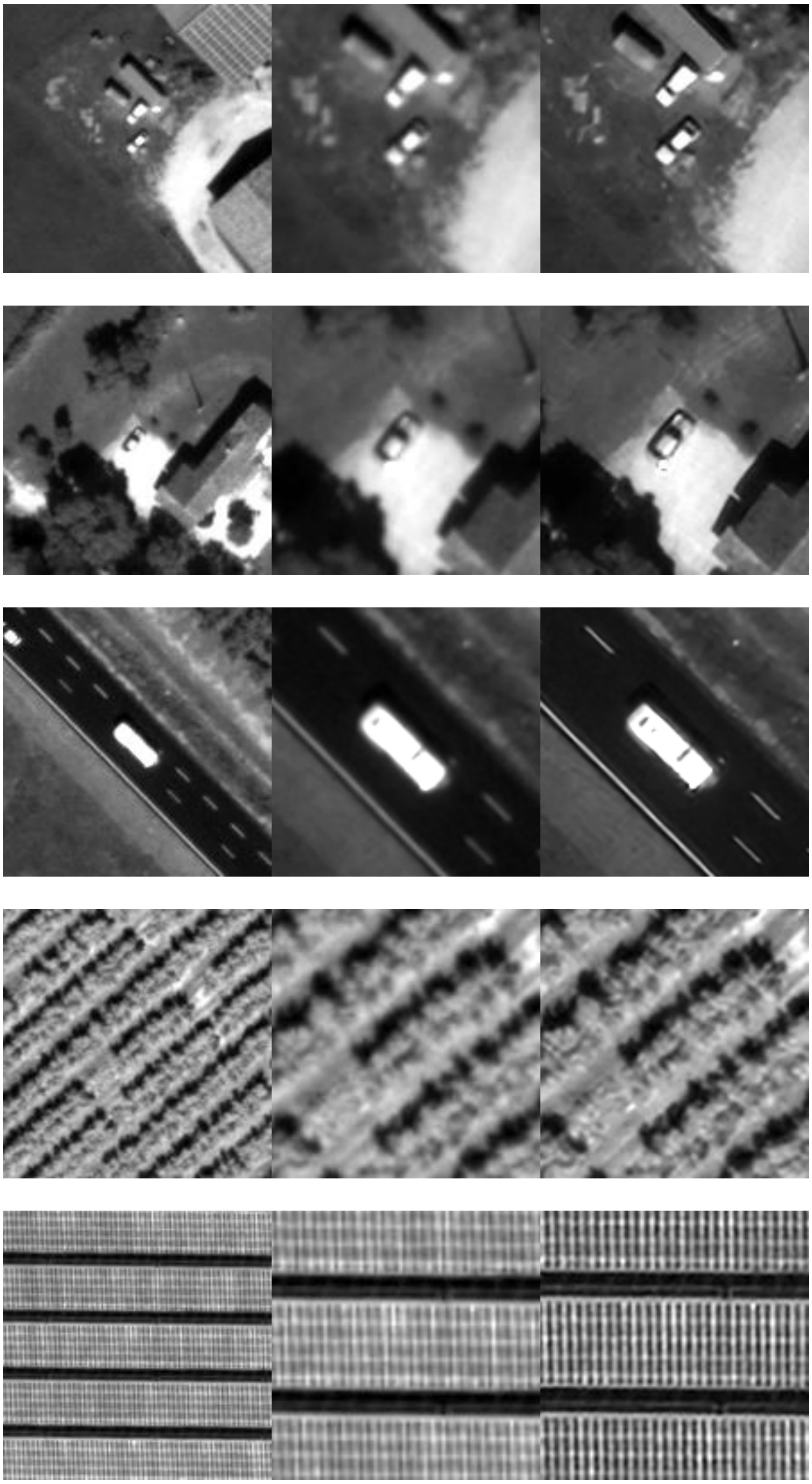


Figure 4-16 France – La Crau POIs: Panchromatic (left) original (0.3 m), (middle) pseudo-HD (0.15 m) and (right) HD (0.15 m) imagery.

The results of this particular comparison indicate the overall visual clarity is improved, as expected, by the HD technology and it demonstrates the latter technology provides more than complex resampling abilities.

4.3.2.3 Results III

The selected points of interest in Munich include railway tracks, a football field, a road and a body of water as shown in Figure 4-17 and Figure 4-18.

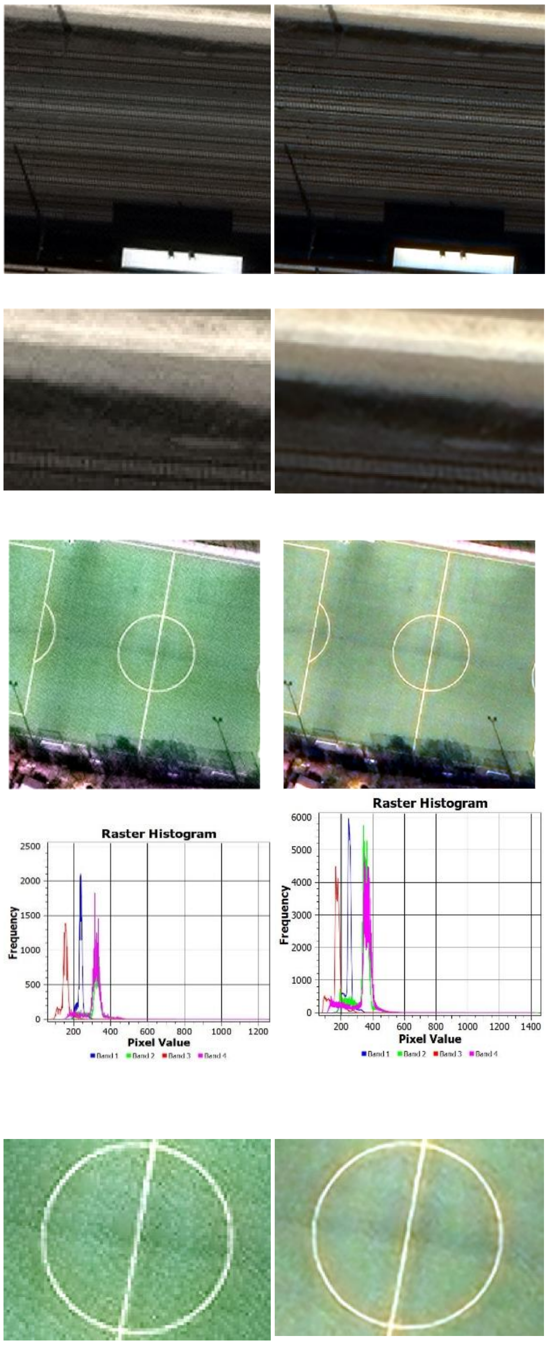


Figure 4-17 Germany – Munich POIs I: (left) Pansharpened RGB MAXAR 30 cm (left) and 15 cm (right) image parts over railway, soccer field and a road in Munich.

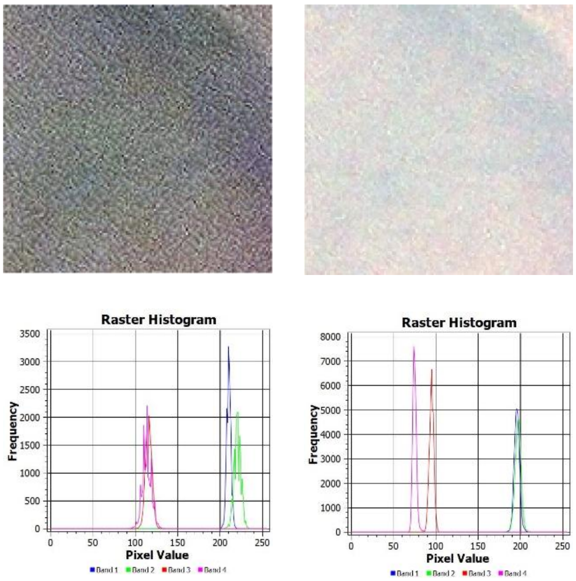


Figure 4-18 Germany – Munich POIs II: MAXAR 30 cm (left) and 15 cm (right) image parts over water surface in Munich.

The results of this particular comparison show more defined railway tracks in the HD product compared to the native product, show colour deformations and over-smoothing (blurring) in the football fields of the HD product, and the vehicles on the road show noise in the HD product. In addition, in Figure 4-18, the imagery of water surfaces, which were displayed with a stretching to minimum-maximum values, and their respective histograms also show over-smoothing in the HD product.

4.3.2.4 Description and Method II

The method used for this assessment was based on comparisons between imagery from WV3 HD products, native WV3 products and aerial Unmanned Aerial Vehicle (**UAV**) products of a suitable test site in Ankara (Turkey). The latter imagery, prior to use, was processed in the following way:

- The optical aerial imagery was acquired using a Sony RX1 RII RGB camera, mounted to a UAV, during a campaign led by the Geomatics Engineering group at Hacettepe University (Turkey) on 11 January 2021. The optical aerial imagery, with an average GSD of 3.25 cm, was used to generate a digital surface model (**DSM**) and then, after performing bundle block adjustment with six GCPs, the DSM was used to generate an orthorectified mosaic of the test site (all shown in Figure 4-19). The green band of the orthorectified mosaic was downsampled to 15 cm using the nearest neighbour resampling kernel to match the HD spatial resolution.
- Note the radiometric resolution of the WV3 and the UAV imagery are 11 bit and 8 bit, respectively, and the comparisons were performed using the imagery displayed with stretching to minimum-maximum values.

The selected POIs in Ankara included a graveyard, a playground, railway tracks and a body of water (shown in Figure 4-20).

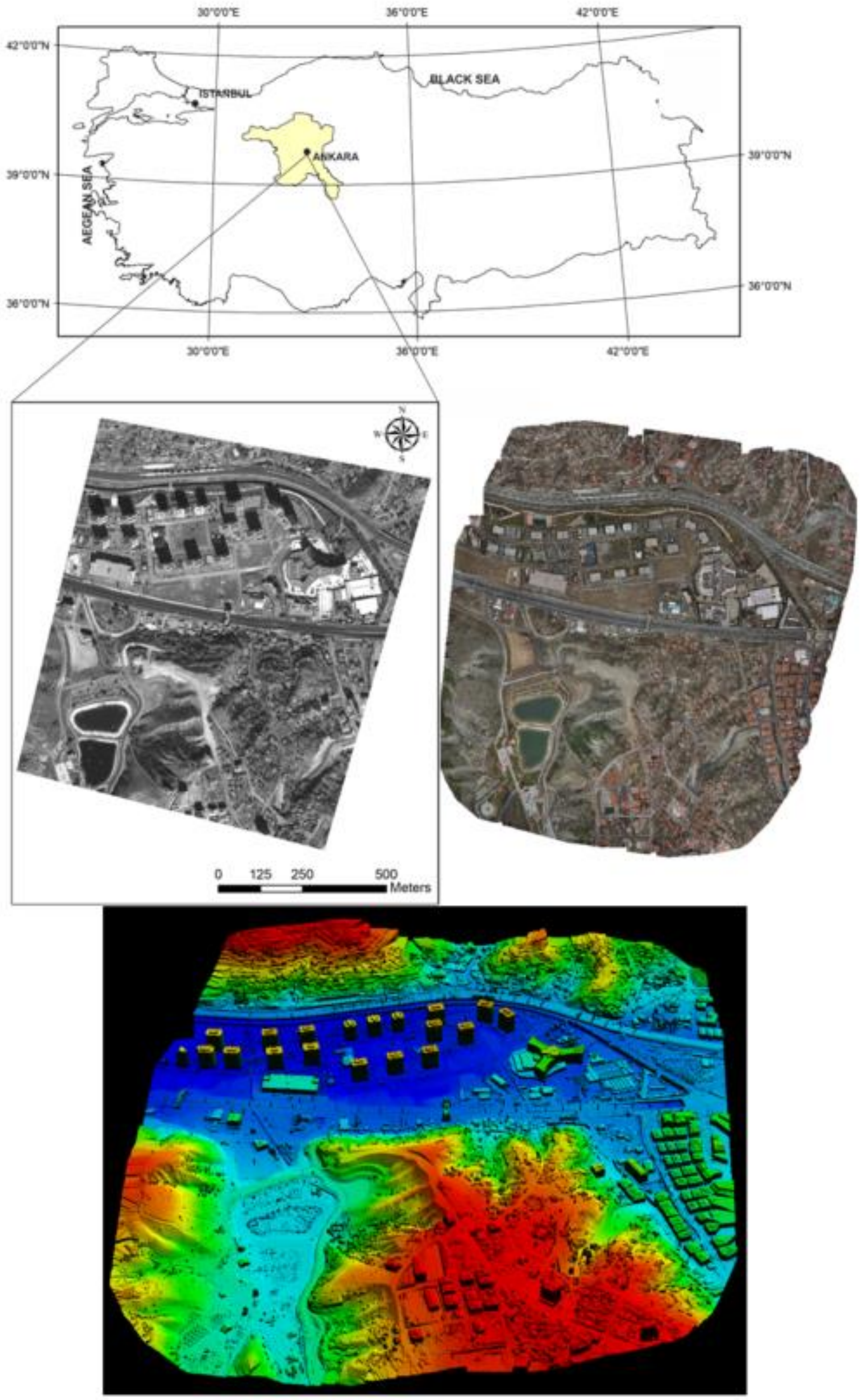


Figure 4-19 The geographic location of the Ankara test site (top), orthorectified HD imagery (middle left), UAV orthorectified imagery (middle right) and the DSM of the test site obtained from the UAV (bottom).

Maxar HD (Panchromatic Band) **UAV (Green band)**

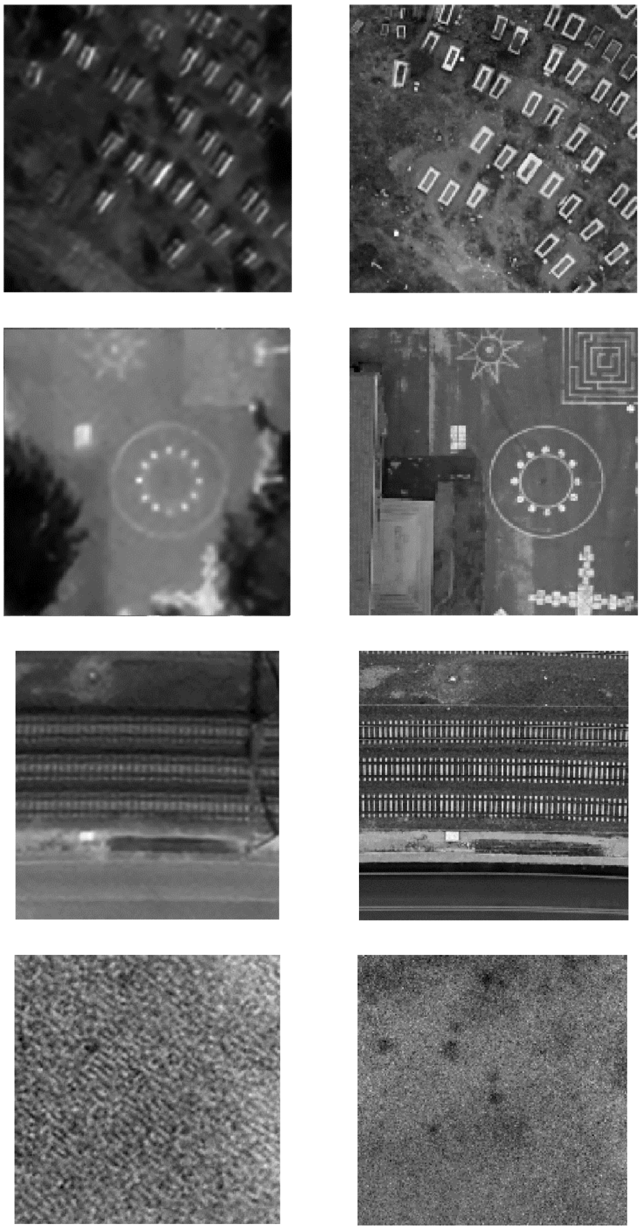


Figure 4-20 MAXAR WV3 HD (left) and UAV (right) image parts over Ankara test site.

The histograms of the WV3 HD imagery over the body of water exhibits random Gaussian noise.

4.3.3 Optional Assessment

Note the assessment presented in this section is deemed optional as it relates to an application of the data.

4.3.3.1 Land Use Land Cover Classification

In order to observe the effect of HD processing on an end-user application such as Land Use / Land Cover (**LULC**) classification, a pixel intensity based image classification method was applied to the Maxar WV3 30 cm and 15 cm imagery for two different sites, which were selected according to the LULC types. The latter sites, for which the data described in Table 4-14 was used, included:

- Gibraltar
  - This site selected was for its urban areas, with sharp edges, and a water body.
- Novi Sad
  - This site was selected for its agricultural areas.

The classification was performed using the random forest method described in [RD-28]. This method is a well-known machine learning classification algorithm based on decision trees.

Table 4-14 Maxar Data for Image Classification Assessment

Product IDs	Product Level	Bands & GSD
• 19NOV24113312-S2AS_R2C1-013396706050_01_P001 • 19NOV24113312-S2AS_R3C1-013396706060_01_P001	LV2A	MS bands native (30 cm) and HD (15 cm)
• 20AUG28094831-S2AS-013396706030_01_P001 • 20AUG28094831-S2AS-013396706010_01_P001	LV2A	MS bands native (30 cm) and HD (15 cm)

The image classification results for the HD products, obtained from the aforementioned sites and are presented in Figure 4-21 - Figure 4-23, generally show an improved classification accuracy. The improved classification accuracy is most likely due to the improved definition of edges provided by the application of the HD technology. However, the latter results also show increased noise over agricultural areas (see Figure 4-22 and Figure 4-23). These findings are in line with those presented in [RD-19].

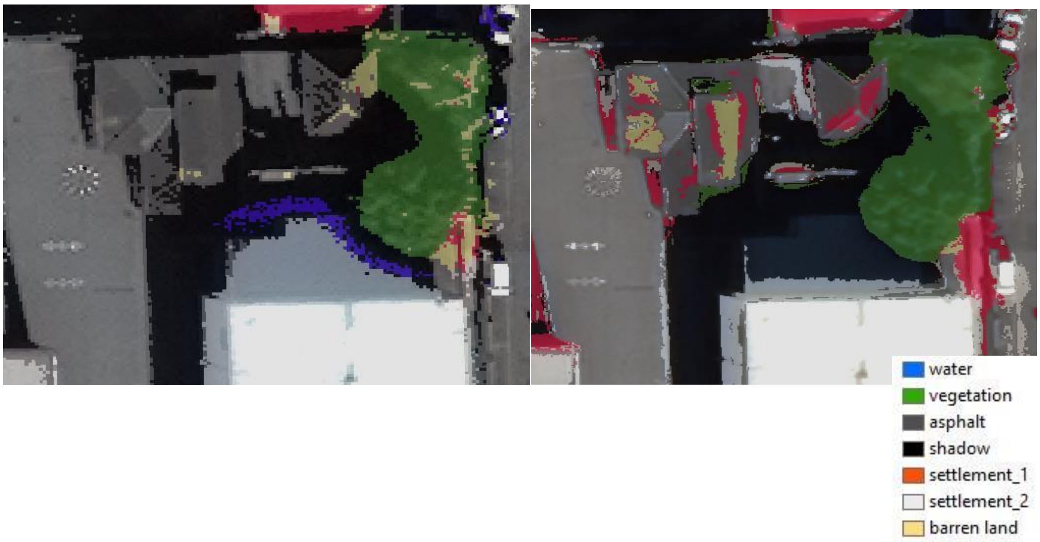
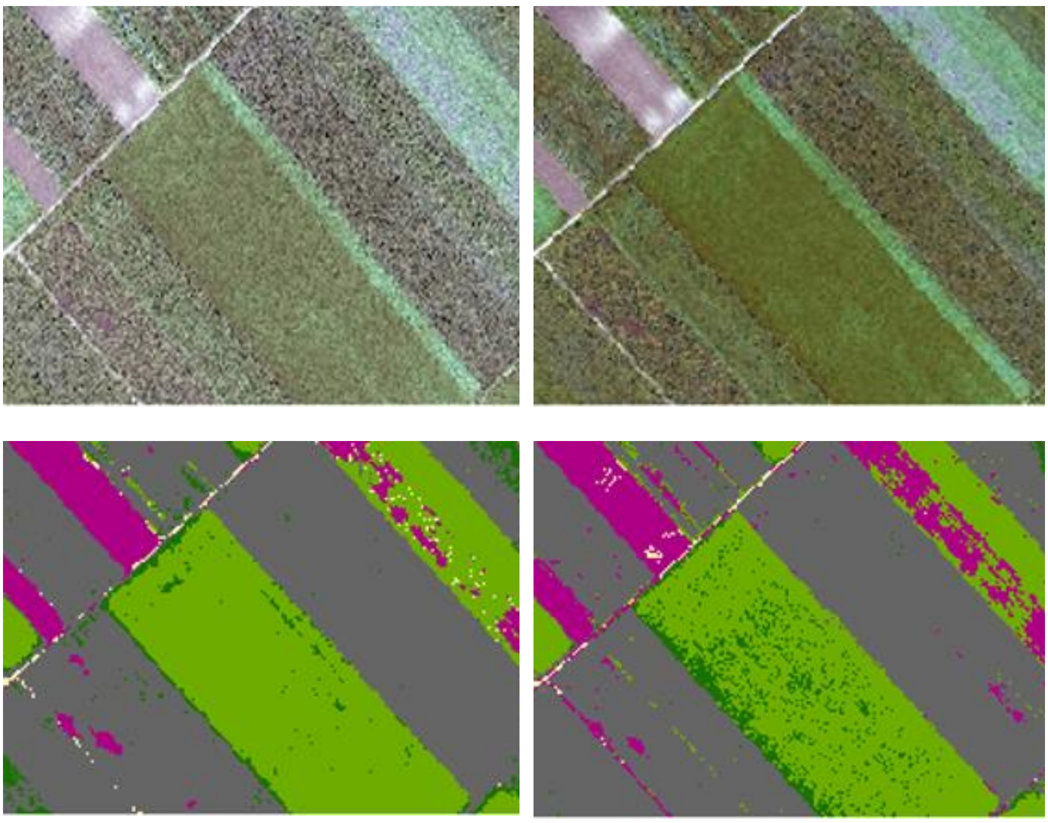


Figure 4-21 Image parts from the image classification results from the 30 cm (left) and 15 cm (right) resolution images over Gibraltar site.



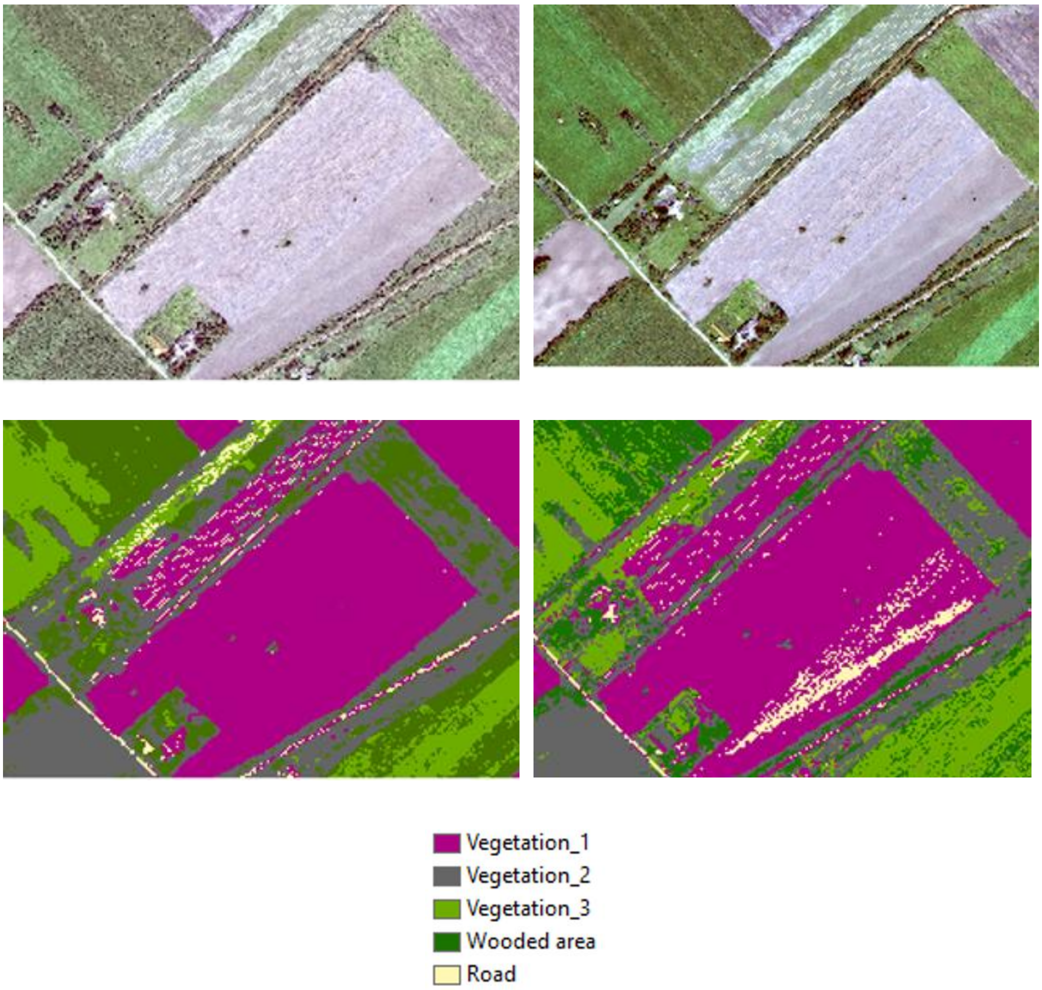
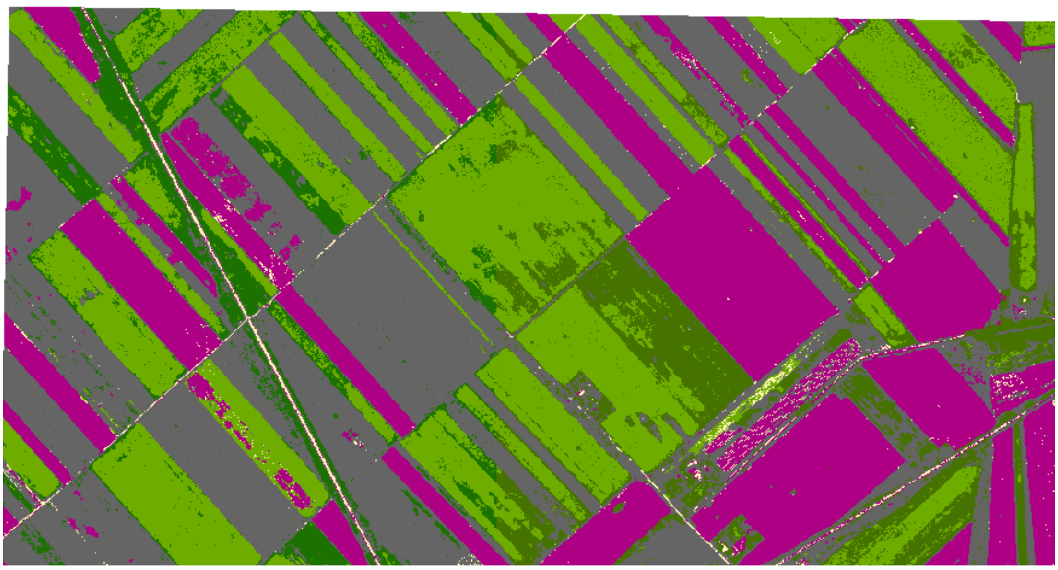


Figure 4-22 Image parts and the classification results from the 30 cm (left) and 15 cm (right) resolution images over Novi Sad site.



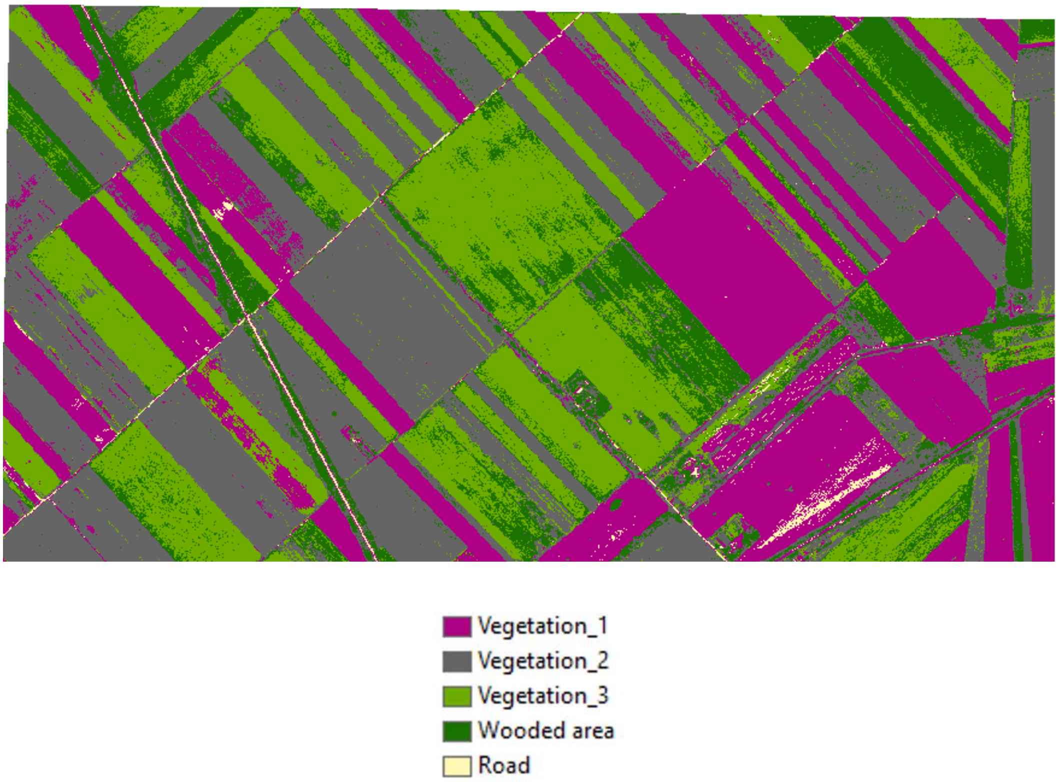


Figure 4-23 Image parts from the image classification results from the 30 cm (top) and 15 cm (bottom) resolution images over Novi Sad site.

CONCLUSIONS

The results of the independent data quality assessments performed here generally indicate the data quality is relatively **good**, based on the following:

- The applied HD technology does not appear to have a negative impact on the **fundamental data quality** (i.e. preservation of geometric and radiometric quality) of the HD products, as expected, when compared to the native products from which they were derived.

- The applied HD technology does provide an improvement in **visual clarity** (interpretability, an aspect of image quality), as stated by Maxar, and therefore enables better image interpretability (e.g. object detection and recognition) that is particularly important to some advanced user applications. There were only relatively minor artefacts, which appeared to be introduced by the technology (as expected with any processing algorithms), that were observed in the product imagery and these included colour deformation and over-smoothing.

It is, however, **strongly recommended** that the mission provider address, at the very least and possibly prior to the release of the products generated by the evolved version of the technology in the near future (as previously reported by Maxar), the following:

- The provision of more detailed documentation on the products (e.g. detailed product description and product specification, algorithms (e.g. HD and pansharpening), and auxiliary data) to allow for users to gain a **clear and sufficient understanding** of these products (this proved challenging, evidenced by the number of assumptions, later verified with the mission provider, that had to be made in order to perform some of the assessments). It is understood that this may be difficult due to the proprietary nature of these products.
- The provision of more detailed product metadata (e.g. additional data quality and traceability information).

5. ANNEX A

Table 5-1 Test Dataset

Product No.	Geographic Location	Product Name
1	La Crau (France)	(HD Bundle) 013518695020_01_P001
2	La Crau (France)	(Native Bundle) 014308801010_01_P001
3	Al Jufra (Libya)	(Native Pansharpened) 013396706040_01_P001
4	Al Jufra (Libya)	(HD Pansharpened) 013396706020_01_P001
5	Al Jufra (Libya)	(HD Bundle) 013615791020_01_P001
6	Munich (Germany)	(HD Bundle) 013396706080_01_P001
7	Munich (Germany)	(Native Bundle) 013396706070_01_P001
8	Ankara (Turkey)	(HD Bundle) 013518695010_01_P001
9	Salon-de-Provence (France)	(HD Bundle) 013518695030_01_P001
10	Gibraltar	(HD Pansharpened) 013396706050_01_P001
11	Gibraltar	(Native Pansharpened) 013396706060_01_P001
12	Novi Sad (Serbia)	(HD Pansharpened) 013396706030_01_P001
13	Novi Sad (Serbia)	(Native Pansharpened) 013396706010_01_P001

[END OF DOCUMENT]