Earth Observation Product Quality Assessment Framework - DEM Guidelines

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1. INTRODUCTION

A Digital Elevation Model (DEM) is a "digital representation of elevations (or height) of a topographic surface in form of a georectified point-based or area-based grid, covering the Earth or other solid celestial bodies" [RD-6]. DEMs began with the systematic measurement of elevation above sea level almost certainly in ancient Egypt [RD-7]. Their usage and creation have been growing over the centuries with the advancements of science. Over the last decades, an ever-increasing number of regional, national and global DEMs have been released publicly. This abundance of data raised the need for comparative DEM product quality evaluations, and consequently, the establishment of standard assessment guidelines for DEMs.

Through the Earthnet Data Assessment Project (EDAP), several sets of guidelines have been defined for the evaluation of Earth Observation (EO) missions and products [RD-1]. However, these guidelines are not directly applicable to DEM products, as DEMs do not currently consist of regular acquisitions, but rather of an aggregation of EO data over extended periods of time (several days to more than a decade). Moreover, fundamental geometry metadata are required to ensure an adequate use of DEMs, including the Coordinate Reference System (CRS), Vertical Reference System (VRS), pixel type (point or area) and grid standard. A bad definition of these metadata cause planimetric and/or vertical shifts, which lead to important biases in elevation comparisons [RD-14]. These characteristics motivated the creation of a set of guidelines dedicated to DEM products.

These guidelines were created with the support of the DEM Intercomparison eXercise (DEMIX) members, a CEOS initiative aiming at providing harmonised terminology and methods, as well as practical guidelines and results allowing the intercomparison of continental or global Digital Elevation Models [RD-8].

1.1 Scope

This document provides guidelines for the evaluation of DEM products. Section 2 provides a summary of the DEM quality assessment framework. Section 3 provides a review of the DEM quality, as evidenced by its documentation. Finally, Section 4 provides guidelines for verifying the DEM product quality is consistent with its stated performance.

1.2 Acronyms & Abbreviations

ARD	Analysis-Ready Data
ATBD	Algorithm Theoretical Basis Document
BBR	Band-to-Band co-Registration
CARD4L	CEOS ARD for Land
CEOS	Committee on Earth Observation Satellites
COCCON	Collaborative Carbon Column Observing Network
CF	Climate & Forecast (Metadata Convention)
CRS	Coordinate Reference System
DEM	Digital Elevation Model

DEMIX	Digital Elevation Model Intercomparison eXercise
DGED	Defense Gridded Elevation Data
DTED	Digital Terrain Elevation Data
DOI	Digital Object Identifier
DSM	Digital Surface Model
DTM	Digital Terrain Model
ECV	Essential Climate Variable
EDAP	Earthnet Data Assessment Pilot
EO	Earth Observation
ESA	European Space Agency
FAIR	Findable, Accessible, Interoperable and Reusable
FRM	Fiducial Reference Measurement
FRM4GHG	Fiducial Reference Measurements for Ground-Based FTIR Greenhouse Gas Observations
FTIR	Fourier Transform InfraRed spectroscopy
GCP	Ground Control Point
GDAL	Geospatial Data Abstraction Library
GeoTIFF	Geographic Tag Image File Format
GIS	Geographic Information System
GPKG	GeoPackage
GSD	Ground Sampling Distance
GUM	Guide to the Expression of Uncertainty in Measurements
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
KML	Keyhole Markup Language
LiDAR	Light Detection and Ranging
L1	Level 1

L2	Level 2
NASA	National Aeronautics and Space Administration
NPL	National Physical Laboratory, UK
PUG/PUM	Product User Guide/Manual
QA4ECV	Quality Assurance Framework for Essential Climate Variables
QA4EO	Quality Assurance Framework for Earth Observation
QGIS	Quantum Geographic Information System
SAR	Synthetic Aperture Radar
SHP	SHaPefile (simple geospatial file exchange format)
SI	Système International (International System of Units)
TCCON	Total Carbon Column Observing Network
URL	Uniform Resource Locator
VHR	Very-High Resolution
VIM	International Vocabulary of Metrology
VRS	Vertical Reference System
WGS84	World Geodetic System 1984
WMO	World Meteorological Organization
XML	eXtensible Markup Language

1.3 Reference Documents

RD-1. EDAP Best Practice Guidelines - Web portal
https://earth.esa.int/eogateway/activities/edap/edap-best-practice-guidelines

RD-2. Earth Observation Mission Quality Assessment Framework, Issue 2.2, 6 December 2022
https://earth.esa.int/eogateway/documents/20142/37627/Mission-Quality-Assessment-Guidelines-v2.2.pdf

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RD-11. Global DEM Quality Assessment Summary, Issue 1.2, 16 July 2020 – VisioTerra https://earth.esa.int/eogateway/documents/20142/37627/Technical+Note+on+Quality+Assessment+for+Global+DEM.pdf/9fe79f57-fbb9-bd13-f32c-03ac2e64179e

RD-12. Copernicus DEMs Quality Assessment Summary, Issue 1.3, 09 November 2021 – VisioTerra https://earth.esa.int/eogateway/documents/20142/37627/Technical+Note+on+Quality+Assessment+for+Copernicus+DEM.pdf/acfe11c2-39c8-b1c9-39c4-1fdba8c1416d

RD-13. VHR DEM Technical Note, Issue 1.1, 29 March 2023 – VisioTerra https://earth.esa.int/documents/d/earth-online/edap-rep-031_1-1-d-22-vhr-dem-technical-note

RD-14. S. Riazanoff et al., Best BiCubic Method to Compute the Planimetric Misregistration between Images with Sub-Pixel Accuracy: Application to Digital Elevation Models. ISPRS Int. J. Geo-Inf. 2024, 13, 96. https://doi.org/10.3390/ijgi13030096

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2. DEM QUALITY ASSESSMENT FRAMEWORK SUMMARY

This section outlines the EO mission quality assessment for Digital Elevation Model (DEM) products. The evaluation is primarily aimed at verifying that DEM products achieve their claimed performance and, where applicable, reviews the extent to which the products follow community best practice in a manner that is "fit for purpose".

The approach taken to assess DEM product quality is based on the QA4EO principle [RD-15] and builds on the structure and reporting style developed in other similar work (e.g.[RD-16]). This quality assessment framework, developed within the ESA Earthnet Data Assessment Project (EDAP+), aims to build on the experience of this previous work targeting the satellite Cal/Val context.

The assessment itself is conducted in two parts, as follows:

- *Documentation Review* – review of DEM product quality as evidenced by its documentation.
- *Detailed Validation* – quantitative assessment of DEM product compliance with stated performance.

These parts of the assessment, along with their grading criteria, are described in Sections 3 and 4, respectively. The activities are divided into sections and subsections constituting each of the different aspects of data product quality that are assessed and graded. Assessment results are provided in a separate Quality Assessment (QA) Report and are also summarised in a colour-coded Cal/Val maturity matrix.

It is expected that all relevant product information needed to perform the assessment would be publicly available to all users, however it is understood that confidentiality may be required for some aspects of a mission. Where this is the case, it will be indicated as confidential in the quality assessment report. In general, pertinent key conclusions of confidential documentation should nevertheless be published openly.

2.1 Product Supply Chain Assessment

The specific DEM product assessment outlined in this document forms part of a wider supply chain assessment. This can be summarised by a Supply Summary Cal/Val Maturity Matrix (Figure 1). This overview matrix encompasses documentation review and detailed validation assessments for all data processing steps for a given DEM product and its primary source of data (generally SAR, optical or LiDAR data).

For each of the rows of the supply chain summary in Figure 1, a full set of EDAP data product quality assessment guidelines exist in the same format as this document. In case no specific guidelines exist for the type of mission covered, the assessment can be performed using the generic EO mission guidelines [RD-2].

To ensure a complete and transparent quality assessment, all products starting from the primary data source of a particular DEM's supply chain should be assessed, wherever possible.

Additional quality assessments performed on the other DEM data sources (used for void filling) may be necessary for the "Ancillary data" assessment (see section 3.2.2).

	Data Provider Documentation Review			Validation Summary
	Product Information	Metrology	Product Generation	
Source Product	Source Product Information	Source Product Metrology	Source Product Generation	Source Product Validation
DEM	DEM Product Information	DEM Product Metrology	DEM Product Generation	DEM Product Validation

Key
Not Assessed
Not Assessable
Basic
Good
Excellent
Ideal
Not Public

Covered by this guideline Also required for a complete assessment

Figure 1 – Supply Chain Summary Matrix and Key. To be colour-coded to report results of assessment.

For some DEM products, several data sources could be considered as "primary" (e.g., DEM products generated from the fusion of several DEMs) and not ancillary data (e.g., DEM or elevation data only used for punctual elevation infills). In such cases, there can be multiple *Supply Chain Summary Matrices*: one for each primary data source identified.

In order to fill the Supply Chain Summary Matrix, "summary grades" should be calculated based on the full Cal/Val maturity matrix of each product of the supply chain (see section 2.3.1 for the case of DEM products). Each "summary grade" can be calculated as the following:

- Convert grades of the assessed category (e.g., Product Information) to numerical equivalents, The "Basic", "Good", "Excellent" and "Ideal" grades correspond to the numerical grades 1, 2, 3 and 4, respectively. Cells which are "Not Assessed" or "Not Assessable" are excluded.
- Calculate the mean of these grades (e.g., grades of "Excellent", "Good", "Basic" and "Basic" are given for "Product Information", which correspond to numerical grades 3, 2, 1, 1 with a mean grade of 1.75).
- Round the mean grade to the closest integer (e.g., a mean grade of 1.75 is rounded to 2).
- Retrieve the grade corresponding to this rounding (e.g., 2 corresponds to a grade of "Good", as given at the first step).

2.2 Quality Assessment Report

The quality assessment for a given DEM product is reported using the QA Report template. The template ensures consistency of reporting and facilitates comparison between DEM product assessments. The QA Report covers each section of analysis, providing more detailed information, as well as including a completed mission Cal/Val maturity matrix (see following subsection) presenting the results of each sub-section of analysis in a colour-coded table.

2.3 Cal/Val Maturity Matrix

A Cal/Val maturity matrix provides a high-level colour-coded summary of the quality assessment results. The matrix contains a column for each section of analysis, and cells for each subsection of

analysis. Subsection grades are indicated by the colour of the respective grid cell, which are defined in the key. A padlock symbol in the corner of given cell indicates that the information used to assess the respective subsection is not available to the public. The reporting of assessment results is divided between two Cal/Val maturity matrices, as follows:

- *Summary Cal/Val Maturity Matrix*
- *Detailed Validation Cal/Val Maturity Matrix*

These matrices are described below.

2.3.1 Summary Cal/Val Maturity Matrix

The *Summary Cal/Val Maturity Matrix* provides an overall summary of the quality assessment results (see Figure 2). The matrix on the left (in dark blue) summarises the results of the *Documentation Review*, while the additional column on the right (in light blue) summarises the results of the *Detailed Validation*. The *Validation Summary* column is separated from the main table to make clear the results can come from multiple assessment sources.

Data Provider Documentation Review			Validation Summary
Product Information	**Metrology[1]**	**Product Generation**	
Product Details	Metrological Traceability Documentation	Calibration Algorithm	Vertical Accuracy Validation Method
Availability & Accessibility	Uncertainty Characterisation	Geometric Processing	Vertical Accuracy Validation Results Compliance
Product Format, Flags & Metadata	Ancillary Data	Retrieval Algorithm	Horizontal Accuracy Validation Method
User Documentation		Additional Layer Processing	Horizontal Accuracy Validation Results Compliance

Key
Not Assessed
Not Assessable
Basic
Good
Excellent
Ideal
Not Public

Figure 2 - Summary Cal/Val Maturity Matrix and Key. To be colour-coded to report results of assessment.[1]

[1] *the scientific study of measurement*

2.3.2 Detailed Validation Maturity Matrix

The *Detailed Validation Cal/Val Maturity Matrix* (see Figure 3) provides more complete reporting of analysis behind the *Validation Summary* – breaking down the validation methodologies used and the results. This section is aimed at the more technically focused reader. Since, for a given DEM product, multiple validation studies may be performed – for example, by the data provider and/or by independent assessors – there can be multiple *Detailed Validation Maturity Matrices* produced and reported.

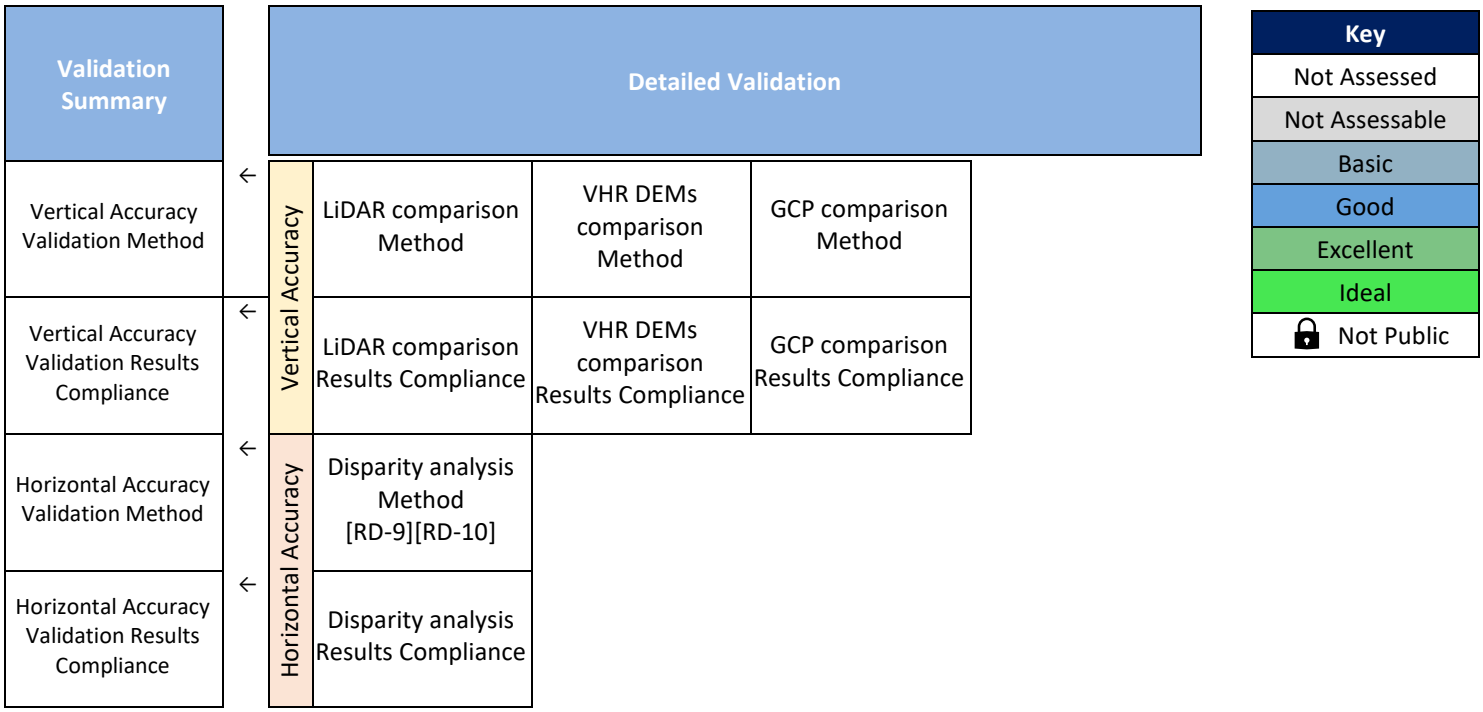

Figure 3 – Validation Cal/Val Maturity Matrix for DEM product validation, which includes the Validation Summary column from the Summary Cal/Val Maturity Matrix

2.4 Approach to Grading

The assessment framework is aimed at verifying the claimed DEM product performance, and that the mission follows community best practice to an extent that is "fit for purpose". The grading criteria for each category are determined based on a logical interpretation of this principle.

The Ideal grade level is generally reserved to provide recognition for achieving the highest standard of quality with respect to community best practice. This high bar of quality may be aspirational but is the benchmark that EO data providers should aim for. Note that a grade of Basic can also be considered acceptable in a given context.

Additionally, a subsection may also indicate Not Assessable or Not Assessed. These cover the cases where certain aspects of product quality will not be assessed – either because there is insufficient information available to make an assessment, or because it is out of scope of the assessment.

3. DATA PROVIDER DOCUMENTATION REVIEW

In this section we provide detailed guidelines for *Documentation Review*. This assessment aims to review the DEM product quality as evidenced by its documentation. It is divided into the follow sections:

- Product Information
- Metrology
- Product Generation

In the following we look at each of these sections in turn and discuss the grading criteria.

The results of the *Documentation Review* are reported on the left portion of the *Summary Cal/Val Maturity Matrix*. This portion is shown in Figure 4.

Data Provider Documentation Review		
Product Information	**Metrology**	**Product Generation**
Product Details	Metrological Traceability Documentation	Calibration Algorithm
Availability & Accessibility	Uncertainty Characterisation	Geometric Processing
Product Format, Flags & Metadata	Ancillary Data	Retrieval Algorithm
User Documentation		Additional Layer Processing

Figure 4 – Data Provider Documentation Review Matrix

3.1 Product Information

The *Product Information* section covers the top-level product descriptive information, product format, and the supporting documentation. Its subsections are now defined.

3.1.1 Product Details

Important characteristics of the DEM product must be specified. These characteristics are given by the following list:

- DEM name / identifier
- Version (date or version number)
- Type (DTM, DSM or other)
- Datatype (Int16, Float32...)
- Ground Sampling Distance (GSD)
- Spatial coverage
- Horizontal datum, including name (e.g., WGS84, ITRS), realization (e.g., WGS84 G1150, ITRF2000)
- Coordinate Reference System
- Vertical datum (name only, e.g., EGM2008)
- Tile grid
- Pixel type (point or area)
- Horizontal accuracy
- Vertical accuracy
- Temporal coverage
- Point of contact (Responsible organisation, including email address)
- Product access (e.g., URL, DOI if applicable)
- Restrictions for access and use, including licence conditions and copyrights
- Lineage (concise information about the creation of the product)

In cases where the elevations of the DEM are derived from another DEM product, at least the DEM identifier and version of this source DEM must be provided.

Additionally, information about the EO mission and products from which the primary elevations have been derived must be provided (i.e., the source radar, optical or LiDAR acquisitions used to generate the primary DEM elevations in the DEM product processing chain). This supplementary information allows to further understand the DEM, from the first acquisitions to the final product. This assessment can be carried out considering the following list of information, extracted from the Earth Observation Mission Quality Assessment Framework [RD-2]:

- Product name
- Sensor Name
- Sensor Type

- Mission Type (Either single satellite or constellation of a given number of satellites)
- Mission Orbit (For example, Sun Synchronous Orbit with Local Solar Time)
- Product version number
- Product ID
- Processing level of product (with reference to the corresponding standard)
- Measured quantity name
- Stated measurement quality (To provide context to the reader for the rest of assessment, provide the product "quality" as specified by the provider)
- Spatial Resolution
- Spatial Coverage (the full swath width and footprint of a scene or single acquisition; define if data's spatial coverage, i.e., if provide global or for specific regions)
- Temporal Resolution (define repeat/revisit time, i.e., time between successive observations of a given location)
- Temporal Coverage Define period of mission operation (expected if current mission)
- Point of contact (Responsible organisation, including email address)
- Product access (e.g., URL, DOI if applicable)
- Restrictions for access and use, if any

As this information is very specific to the mission and not to the DEM product, it is not mandatory that the DEM documentation clearly states these characteristics. This information may be found in links or web pages given as reference in the DEM documentation.

Table 3-1 – Product Information > Product Details – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside of the scope of study.
Not Assessable	Relevant information not made available.
Basic	Some of the DEM product characteristics are missing.
Good	All the DEM product characteristics are available, no information is available on the primary instrument / mission from which the DEM has been generated
Excellent	All the DEM product characteristics are available, some information is available for the primary instrument / mission from which the DEM has been generated.
Ideal	All the DEM product and primary instrument / mission characteristics are available.

3.1.2 Availability & Accessibility

DEM products are expected to be accessed, downloaded and used easily. This assessment is done by referring to the FAIR (Findable, Accessible, Interoperable, Reusable) Data Principles for scientific data management and stewardship [RD-4], which provide valuable principles for all data applications. These generic principles state the following:

Data should be findable

- Metadata and data are assigned a globally unique and persistent identifier
- Data are described with rich metadata
- Metadata clearly and explicitly include the identifier of the data it describes
- Metadata and data are registered or indexed in a searchable resource

Data should be accessible

- Metadata and data are retrievable by their identifier using a standardised communications protocol
- The protocol is open, free and universally implementable
- The protocol allows for an authentication and authorisation procedure where necessary

Data should be interoperable

- Metadata and data use a formal, accessible, shared and broadly applicable language for knowledge representation
- Metadata and data use vocabularies that themselves follow FAIR principles
- Metadata and data include qualified references to other (meta)data

Data should be reusable

- Metadata and data are richly described with a plurality of accurate and relevant attributes
- Metadata and data are released with a clear and accessible data usage license
- Metadata and data are associated with detailed provenance
- Metadata and data meet domain-relevant community standards

Table 3-2 shows how a data product's provision of the above information relates to the grade it achieves for this sub-section of the quality assessment.

Table 3-2 – Product Information > Availability and Accessibility – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	Relevant information not made available.
Basic	The DEM product does not appear to be following the FAIR principles.
Good	The DEM product meets many of the FAIR principles and/or there is an associated data management plan that shows progress towards the FAIR principles.
Excellent	The DEM product meets many of the FAIR principles and has an associated data management plan and is available either free of cost or through an easy-to-access commercial licence.
Ideal	The DEM product fully meets the FAIR principles and has an associated data management plan and is available either free of cost or through an easy-to-access commercial licence.

3.1.3 Product Format, Flags and Metadata

Metadata and ancillary layers/masks are essential to the interpretation of DEM products. In addition to the use of standard formats, it is required that the DEM product includes associated layers/masks which are easily visualized and/or processed in standard GIS tools. This evaluation is based on the following points:

- whether ancillary DEM layers are available. Layers may include superimposable images (e.g., source data mask, land/water mask, editing mask, sample number mask...) or polygons (e.g., source scenes used to generate the primary DEM data). These layers are not required to be archived with the DEM elevations directly. In this case, the location where users can find such layers should be clearly indicated (e.g., links in the user manual or webpage(s) of the product),
- whether DEM product metadata are available (e.g., DEM identifier, version, footprint of the tile, geometry). Metadata should be found close to the DEM layers they qualify (either directly archived with the DEM product or as a separate file easily findable).
- whether a standard file format is used both for DEM layers and metadata. Examples include, but are not limited to: - GeoTIFF for images, -KML or GeoPackage (GPKG) for polygons, -XML for metadata. Additionally, if the DEM is only downloadable as an archive, a widely known and non-proprietary compression format should be used (e.g., zip, tar.gz)
- whether a standard metadata convention is used. Usually, such convention is directly given as a field in the metadata files or directly in the user guide / manual.

Table 3-3 shows how a given DEM product should be graded for its format.

Table 3-3 – Product Information > Product Format, Flags and Metadata – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	Non-standard, undocumented data format.
Basic	The DEM is provided in a non-standard or proprietary data format, or poorly documented standard format. No or minimal / poorly documented metadata available. No relevant ancillary layer.
Good	The DEM is provided in a documented standard file format (including archive format, if applicable). Crucial geometry metadata included (CRS, VRS, product spatial extent, point/area pixel representation). Information about the processing of the DEM (source acquisitions, infills, editions, elevation errors) is available in metadata files (product level), but not as additional layers (tile or pixel level).
Excellent	The DEM is provided in a documented standard file format (including archive format, if applicable). Rich metadata available, including information about the DEM, its geometry and the provider. A set of metadata files (at product level) and additional layers (at pixel level) inform about the processing of the DEM (source acquisitions, infills, editions, elevation errors).
Ideal	The DEM is provided in a documented standard file format (including archive format, if applicable). Rich metadata available, following a standard metadata convention. A set of well documented ancillary layers give information about the processing of the DEM at pixel level, including source acquisitions (polygons and/or number of acquisitions), infills from external data, editions of the DEM (e.g., interpolation, flattening) and elevation errors.

3.1.4 User Documentation

DEM products are required to be delivered with a proper documentation, which includes a Product User Guide (PUG) or Product User Manual (PUM) and an Algorithm Theoretical Basis Document (ATBD).

Regarding the PUG / PUM, the following information should be included:

- All the product details (see section 3.1.1)
- Structure of the product, including the different directories, files (layers, metadata) and their naming convention
- Metadata fields description. This description is not mandatory if the metadata follows a standard convention. In this case, a link or reference to the metadata standard convention must be provided
- Layers description, including the meaning of each value for masks, and a clear definition of the quantity measured for regular layers

Regarding the ATBD, the following information should be included:

- Input EO product characteristics (radar, optical, LiDAR dataset), including (if applicable) the product name and version which has been used to generate the DEM
- DEM generation methods, usually including the elevation retrieval, elevation calibration and tile merging / resampling methods

Table 3-4 describes how the assessment framework grades a products user documentation.

Table 3-4 – Product Information > User Documentation – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	No user documentation provided or documentation out-of-date.
Basic	Limited PUG available, no ATBD. Information is up-to-date.
Good	Some PUG and ATBD-type information available. These may be formal documents or from multiple sources. Documentation is up-to-date.
Excellent	PUG contains all the required information, reasonable ATBD covering most of the required information. Documentation is up-to-date.
Ideal	PUG and ATBD cover all the required information. Documentation is up-to-date.

3.2 Metrology

Metrology is the science of measurement. This section covers the aspects of the mission related to measurement quality, including calibration, traceability and uncertainty. The Metrology subsections are now defined.

3.2.1 Metrological Traceability Documentation

Traceability is defined as a “property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty” in the International Vocabulary of Metrology (VIM, [RD-5]). Various diagrammatic approaches have been developed to present the traceability chains for EO data products (e.g. the QA4ECV guidance, which includes a traceability chain drawing tool [RD-17]).

DEMs are usually generated from SAR (interferometry), optical (photogrammetry), LiDAR (point cloud aggregation), acoustic (sonar) missions, or even by the fusion and edition of several EO products (including existing DEMs). The horizontal and vertical accuracies of a DEM are directly impacted by the uncertainties of these input EO products. The DEM documentation is only expected to provide the traceability chain from the end generation process of the primary

source(s) of data (SAR, optical or LiDAR products) to the generation of the DEM product (e.g., interferometry, photogrammetry, point cloud aggregation…). However, if possible, the grading should take into account the full product supply chain, including the primary data source(s) generation. This requires the assessment of the primary source(s) of data and its / their different levels of product as well (see section 2.1).Table **3-5** shows how the assessment framework grades the metrological traceability documentation, based on its completeness.

Table 3-5 – Metrology > Metrological Traceability Documentation – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	No traceability chain documented.
Basic	Traceability chain diagram and/or uncertainty tree diagram included, missing some important steps.
Good	Traceability chain and/or uncertainty tree diagram documented identifying most important steps and sources of uncertainty.
Excellent	Rigorous uncertainty tree diagram, with a traceability chain documented, identifying all reasonable steps and accompanying sources of uncertainty.
Ideal	Rigorous uncertainty tree diagram and traceability chain documented, identifying all reasonable steps and accompanying sources of uncertainty. Establishes traceability to SI.

3.2.1 Uncertainty Characterisation

To ensure measurements are both meaningful and defensible, it is crucial that they include rigorously evaluated uncertainty estimates. A comprehensive description of how to evaluate sources of uncertainty in a measurement, and propagate them to a total uncertainty of the final measurand, is provided by the metrological community in the Guide to the Expression of Uncertainty in Measurement (GUM) [RD-18].

Similarly to the “Metrological Traceability Documentation”, DEM documentation is only expected to provide uncertainties from the primary source(s) of data (SAR, optical, LiDAR, DEM products) to the generation of the DEM product. However, the grading should take into account the full product supply chain, including the primary data source(s) generation (see section 2.1). This includes the primary source product uncertainties and their propagation to the DEM product generation. Products not considered as a “primary” data source (e.g., only used for void-filling or other additional processes) should not be included in this assessment, but evaluated in the “Ancillary data” section (see section 3.2.2).

Table 3-6 shows the uncertainty characterisation grading under the assessment framework.

Table 3-6 – Metrology > Uncertainty Characterisation – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	No uncertainty information provided.
Basic	Uncertainty established by limited comparison to elevations from other elevation products (VHR DEMs, LiDAR elevations, GCP…) and/or limited uncertainty estimate for the primary data source of the DEM.
Good	Limited use of rigorous uncertainty estimation approaches, and/or, an expanded comparison to elevations from other elevation products. Most important sources of uncertainty are included, both for the DEM and the primary data source.
Excellent	Metrologically rigorous approach used to estimate measurement uncertainty, all important sources of uncertainty are included, both for the DEM and the primary data source.
Ideal	Metrologically rigorous approach used to estimate measurement uncertainty, all important sources of uncertainty are included, both for the DEM and the primary data source. Uncertainty per pixel provided.

3.2.2 Ancillary Data

Throughout the processing chain there may be a requirement for external input data, for example, reference elevation data (e.g., LiDAR or Ground Control Points) for DEM calibration, water body treatment or void filling. The ancillary datasets used during the processing should be identified to the user (where possible due to commercial sensitivity). The requirements are specific to the retrieval method used and may require some expert judgement.

Table 3-7 shows how the ancillary data are graded under the assessment framework.

Table 3-7 – Metrology > Ancillary Data – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	Use of ancillary data undocumented.
Basic	Ancillary data used in DEM product generation, available to some extent, though incomplete. Not entirely of a sufficient quality to be judged “fit for purpose” in terms of the DEM’s stated accuracy.
Good	Ancillary data used in DEM product generation, available, though not necessarily on a per DEM tile basis. Mostly of a sufficient quality to be judged “fit for purpose” in terms of the DEM’s stated accuracy.
Excellent	Ancillary data used in DEM product generation, fully available per DEM tile, and traceable. Ancillary data used are of sufficient quality to be judged “fit for purpose” in terms of the DEM’s stated accuracy.
Ideal	Ancillary data used in DEM product generation, meets the Excellent criteria, and are traceable to SI where appropriate.

3.3 Product Generation

The Product Generation section covers the processing steps undertaken to generate the DEM product. This primarily concerns the calibration algorithm, the geometric processing, the product and ancillary layers generation.

3.3.1 Calibration Algorithm

As previously mentioned, DEM elevations are generated from diverse techniques depending on the nature of their primary input data .In the case of DEM products, the calibration activity is a crucial step which aims to correct potential altimetric biases and/or planimetric misregistrations in the generated elevations. This activity may rely on existing elevation datasets (GCPs, LiDAR, existing DEMs), acting as altimetric and/or planimetric references in the calibration process.

The quality and accuracy of the reference data and the relevance of the methodology used for this calibration must be assessed. This information is found in the ATBD of the DEM product. The grading is based on the quality and representativeness of the input data, as well as the algorithms used to perform the calibration.

Table 3-8 shows how the calibration algorithm is graded under the assessment framework.

Table 3-8 - Product Generation > Elevation Retrieval & Calibration Algorithm – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	Additional processing steps not documented.
Basic	Calibration is poorly documented for the DEM and/or primary data source. External reference data (if applicable) is deemed of insufficient quality.
Good	Calibration is well documented for the DEM. A simple DEM calibration algorithm is applied, limited to the vertical axis (z-axis). External data (if applicable) is deemed of sufficient quality, accuracy and representativeness to be used as a reference.
Excellent	Calibration is well documented. An advanced DEM calibration algorithm is applied, encompassing both the vertical (z-axis) and planimetric (x-axis and y-axis) axes. External data is well documented, deemed of sufficient quality, accuracy and representativeness to be used as a reference.
Ideal	Calibration is well documented. An advanced DEM calibration algorithm is applied, encompassing both the vertical (z-axis) and planimetric (x-axis and y-axis) axes. External data is well documented, deemed independent of the DEM, and of sufficient quality, accuracy and representativeness to be used as a reference. The reference product acquisition date(s), level(s), version(s) and number of samples used are precisely described in the ATBD.

3.3.1 Geometric Processing

The geometric processing involves all the steps required to retrieve DEM elevations at the correct locations, with respect to a specific Coordinate Reference System (CRS) and Vertical Reference System (VRS). This generally consists of transformations applied to convert the data source(s) to the target geometry of the DEM. Ideally, the source and target CRS and VRS should be mentioned,

with precise documentation explaining the methods, reference data and / or tools used to perform this conversion, such as:

- Conversion or transformation grids – grids of conversion / transformation allowing to convert from a CRS and/or VRS to another (e.g., geoid height grids or datum change grids).
- Transformation models and parameters – Equations and their given parameters allowing to transform coordinates between two different CRS and/or VRS (e.g., projection methods, datum changes methods such as the Helmert transform).
- Transformation software – Either generic GIS or specific software used to perform transformations (e.g., QGIS, GDAL or custom solution).

Table 3-9 shows how geometric processing is graded under the assessment framework.

Table 3-9 - Product Generation > Geometric Processing – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	Geometric processing not documented.
Basic	Geometric processing of the DEM documentation mentions at least the DEM CRS and VRS, but no clear information on the primary source data geometry, the transformations or data / tools (if applicable) used for this process.
Good	Geometric processing of the DEM is briefly documented, stating the primary data source and target DEM geometries and identifying the main transformations and associated data / tools (if applicable). The overall planimetric and / or vertical uncertainty resulting from this chain of transformations is stated, but not on a per-transformation basis.
Excellent	Geometric processing of the DEM is clearly documented, identifying all the steps and data / tools required to register the DEM in its target geometry from the primary data source. The planimetric and / or vertical uncertainty resulting from this chain of transformations are stated for each individual transformation.
Ideal	Geometric processing of the DEM is clearly documented, identifying all the steps and data / tools required to register the DEM in its target geometry from the primary data source. The planimetric and / or vertical uncertainty resulting from this chain of transformations are stated for each individual transformation, also including the ancillary data used (if any) for infills or other processes impacting the DEM product quality.

3.3.2 Retrieval Algorithm

Retrieval algorithm covers all the processing used to generate the final DEM elevations layer, including elevation generation, void masking and/or filling with “manual” edits, interpolation, use of external data, building / canopy removal (DTM only), mosaicking or any other process dedicated to the generation of the elevations layer of the DEM product.

In case the final product is divided into multiple files, the algorithm is expected to produce consistent DEM tiles, and maintain the continuity of pixels between neighbour tiles. Some discontinuities between tiles may be accepted if they originate from a reasonable choice of the provider (e.g., different latitude zones for "geographic" DEMs) ,an unavoidable constraint (e.g., change of projection to avoid deformations), or the use of a standard grid (e.g., the Defense Gridded Elevation Data defines standard zones with different resolutions).

The gradation is dependent on the type of instrument and its known limitations, the robustness of the methods as well as the standards used for the generation of the DEM product. These criteria may require some expert judgement.

Table 3-10 – Product Generation > DEM Generation Algorithm – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	DEM generation algorithm is not documented or the documentation is not available.
Basic	Poor elevation retrieval method, not taking into account the instrument or acquisition limitations, leading to artifacts in the DEM elevations (no masking or void value). Inconsistent DEM tiling and / or no continuity between neighbour DEM tiles (unaligned pixels).
Good	Simple elevation retrieval methods, taking into account the instrument or acquisition limitations, with no strategy for infill (void values in the DEM) or lack of documentation about infill procedures. Consistent DEM tiling and continuity ensured between neighbour DEM tiles (aligned pixels).
Excellent	Intermediate elevation retrieval methods, taking into account the instrument or acquisition limitations, using reasonable and documented strategies for filling some of the voids (multiple dates of acquisition or editing). Precise break down of the generation algorithm steps as text or flow chart. If applicable, consistent DEM tiling and continuity ensured between neighbour DEM tiles (aligned pixels).
Ideal	Advanced elevation retrieval methods, taking into account the instrument or acquisition limitations, using "fit-for-purpose" and documented strategies for filling all the voids (e.g., use of multiple acquisition dates, editing, external data of high quality and accuracy). Precise break down of the generation algorithm steps (text or flow chart), use of a standard grid system (DGED, DTED…) for tiling.

3.3.1 Additional Layer Processing

DEM products are usually provided with various superimposable layers, which have been derived from the original DEM elevations and/or external datasets. The goal of this section is to assess the quality and the relevance of the algorithms and data used to compute these additional layers. No generic guidelines could encompass the wide variety of layers (and associated algorithms / external data) that could derivate from DEMs. However, the following questions may help defining the criteria of evaluation for each algorithm:

- Is the algorithm clearly documented?
- Can the algorithm be considered as "fit for stated purpose" (e.g., for masks, the algorithm/method ensures an accurate classification)?

Similarly, the following questions could be helpful for external data:

- Is the external data clearly identified (product identifier, version...)?
- Is the external data well documented (main purpose and limitations)?
- Can the external data be considered as "fit for stated purpose" (sufficient quality, resolution...)?

Table 3-11 – Product Generation > Ancillary Layers Processing – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	Ancillary layers processing is not documented or the documentation is not available.
Basic	Ancillary layers generation methods are documented, but the algorithm / methods or external data are not considered fit for stated purpose.
Good	Ancillary layers generation methods are documented, but some of the steps of the algorithm / methods or some of the external data are not considered fit for stated purpose.
Excellent	Ancillary layers generation methods are documented, and all the steps of the algorithm / methods and the external data are considered fit for stated purpose.
Ideal	Ancillary layers generation methods are documented, and all the steps of the algorithm / methods and the external data are considered state-of-the-art.

4. DETAILED VALIDATION

In this section we provide guidelines for the *Detailed Validation* assessment. The overall goal here is to verify that the results of the validation are consistent with the stated DEM accuracy.

The detailed validation assessment is broadly divided into the validation methodology, and the validation results compliance. The validation method assessment is further divided into three sub-categories; the validation dataset, method, and completeness. The results are reported as part of the *Detailed Validation Cal/Val Maturity Matrix* (Figure 5) and are then summarised across all performance metrics in the *Validation Summary*. This *Validation Summary* is the same summary presented as a column in the *Summary Cal/Val Maturity Matrix* shown in Figure 2.

The remainder of this section includes:

- The criteria for grading the quality of the validation methodology, including the validation dataset, method, and completeness is given in Section 4.1
- Assessment of the compliance of the product with the validation activity is outlined in Section 4.2

Finally, in Section 4.3 the approach for synthesising the results of the *Detailed Validation* into the *Validation Summary* is described.

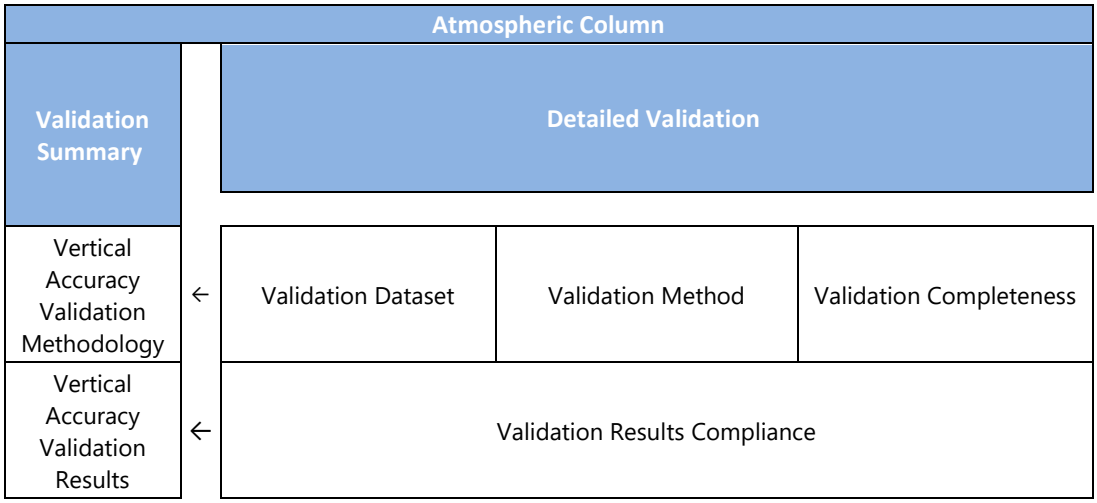

Figure 5 – Detailed Validation Cal/Val Maturity Matrix and Validation Summary

4.1 Validation Methodology

This section describes how, in generic terms, the criteria for grading the quality of the Validation Methodology, including the technique used, the validation approach (how mature and state-of-the-art the method is), and the completeness of the validation.

4.1.1 Validation Dataset

The validation is a crucial step in which the accuracy of the DEM is assessed. This activity usually relies on reference elevation data, which may come in various forms (e.g., Ground Control Points, LiDAR dataset).

The quality of the reference data can be estimated from the following questions:

- Are the reference product identifier and version stated?
- Can the external data be considered as a reference?
- Is the reference data independent of the DEM product?
- Is the reference data sufficiently documented? This should include mission calibration / validation activities, as well as a clear product documentation.
- Is the reference data covering the spatial extent of the DEM?
- In the case of reference points (GCP or LiDAR),
  - has the reference dataset a sufficient point density?

Are the points regularly spaced?

Table 4-1 shows how the validation technique is graded. The specific interpretation of these criteria in the quality assessment of a particular validation activity depends on a number of factors, therefore some level of expert judgement may be required when determining the grading.

Table 4-1 – Validation > Validation Dataset – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	No validation activity performed.
Basic	Limited information about the validation data.
Good	Data suitable for the validation of the DEM product, but not representative of the DEM product (differences of spatial and temporal extent).
Excellent	Data suitable for the validation of the DEM product. Spatiotemporal mismatches are fully considered. Validation data may have partially been used in the generation of the DEM product (void filling).
Ideal	Data suitable for the validation of the DEM product. Spatiotemporal mismatches are fully considered and the validation data has not been used for the generation or calibration of the DEM.

4.1.2 Validation Method

As previously stated (see section 4.1.1), the DEM validation activity usually relies on reference elevation data, which may come in various forms (e.g., Ground Control Points, LiDAR dataset). Both elevation sources are compared with regards to a validation method, including potential filtering and/or transformations of the data and comparison algorithms. The quality of the validation method can be estimated from the following questions:

- Are the reference data and/or DEM product transformed to be expressed in the same reference systems (horizontal and vertical datums)?
- Is the reference dataset corrected and/or filtered?
- Are the comparison statistics relevant for elevation differences?.

Table 4-2 shows how the validation approach is graded within the assessment framework.

Table 4-2 – Validation > Validation Method – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	No validation activity performed.
Basic	Basic/outdated validation method, providing one set of validation statistics for the whole DEM product. Few information on the processing steps of data.
Good	Validation method with proven track-record. Documentation about the different processing steps of the validation.
Excellent	Mature validation method that is considered state-of-the-art. Rich information about the input products (validation and DEM) and their processing.
Ideal	Mature validation method that is considered state-of-the-art. Perfectly reproducible validation method, based on extensive documentation of the products, their pre-treatments and methods for comparing elevations.

4.1.3 Validation Completeness

Based on the validation dataset (see section 4.1.1) and method (see section 4.1.2), this section aims to assess the completeness of the validation process. A validation process can be deemed complete if both the reference data and the methodology are suitable for the evaluation of the DEM product. The grading is based on the quality and suitability of the reference data, the extent to which the validation process has been performed, as well as the quality of results and analyses.

Table 4-3 shows how the validation completeness is graded within the assessment framework.

Table 4-3 – Validation > Validation Completeness – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	No validation activity performed.
Basic	Limited validation e.g. limited to a specific spatial extent not representative of the whole DEM product. Few statistics and/or only at a product level.
Good	Validation activity carried out on most of the DEM spatial extent. Allowance for some gaps in spatial coverage and temporal mismatch with reference data. Validation statistics divided into several areas (continents, countries…).
Excellent	Validation activity carried out on most of the DEM spatial extent. Appropriate temporal coverage. Validation statistics available on a regular grid or per tile.
Ideal	Validation activity carried out on most or all of the DEM spatial extent. Appropriate temporal coverage. Validation statistics available on a regular grid or per tile. Advanced analysis of the sources of uncertainties with regard to other layers or external data (e.g., influence of the land use/cover on elevation differences)

4.2 Validation Compliance

This section assesses the actual results of the DEM validation activities. Grading for this subsection is based on the compliance of the validation results with the performance claimed by the DEM data provider, usually defined as vertical and horizontal accuracies (usually, linear / circular errors).

Table 4-4 shows how the validation results are graded within the assessment framework.

Table 4-4 – Validation > Validation Compliance – Assessment Criteria

Grade	Criteria
Not Assessed	Assessment outside the scope of study.
Not Assessable	No validation activity performed.
Basic	Claimed DEM accuracies show some agreement with validation results.
Good	Claimed DEM accuracies show good agreement with validation results.
Excellent	Claimed DEM accuracies show excellent agreement with validation results. Analysis performed independently of the DEM product owner.
Ideal	Claimed DEM accuracies show excellent agreement with validation results, uncertainties also validated. Analysis performed independently of the DEM product owner.

4.3 Validation Summary

The Validation Summary provides a synthesis of the per performance metric assessments provided in the Detailed Validation Cal/Val Maturity Matrix (Figure 5). It is also presented as part of the *Summary Cal/Val Maturity Matrix*.

Each row in the *Detailed Validation Cal/Val Maturity Matrix* is represented by one cell in the *Validation Summary* column. Thus, there are two summary cells in total – Vertical Accuracy Validation Methodology and Vertical Accuracy Validation Compliance. The grade for each of these summary cells represents a combination of the grades of the contributing cells. The approach is to effectively average the grades of the contributing cells, where each grade is valued as follows: Basic is 1, Good is 2, Excellent is 3, and Ideal is 4.