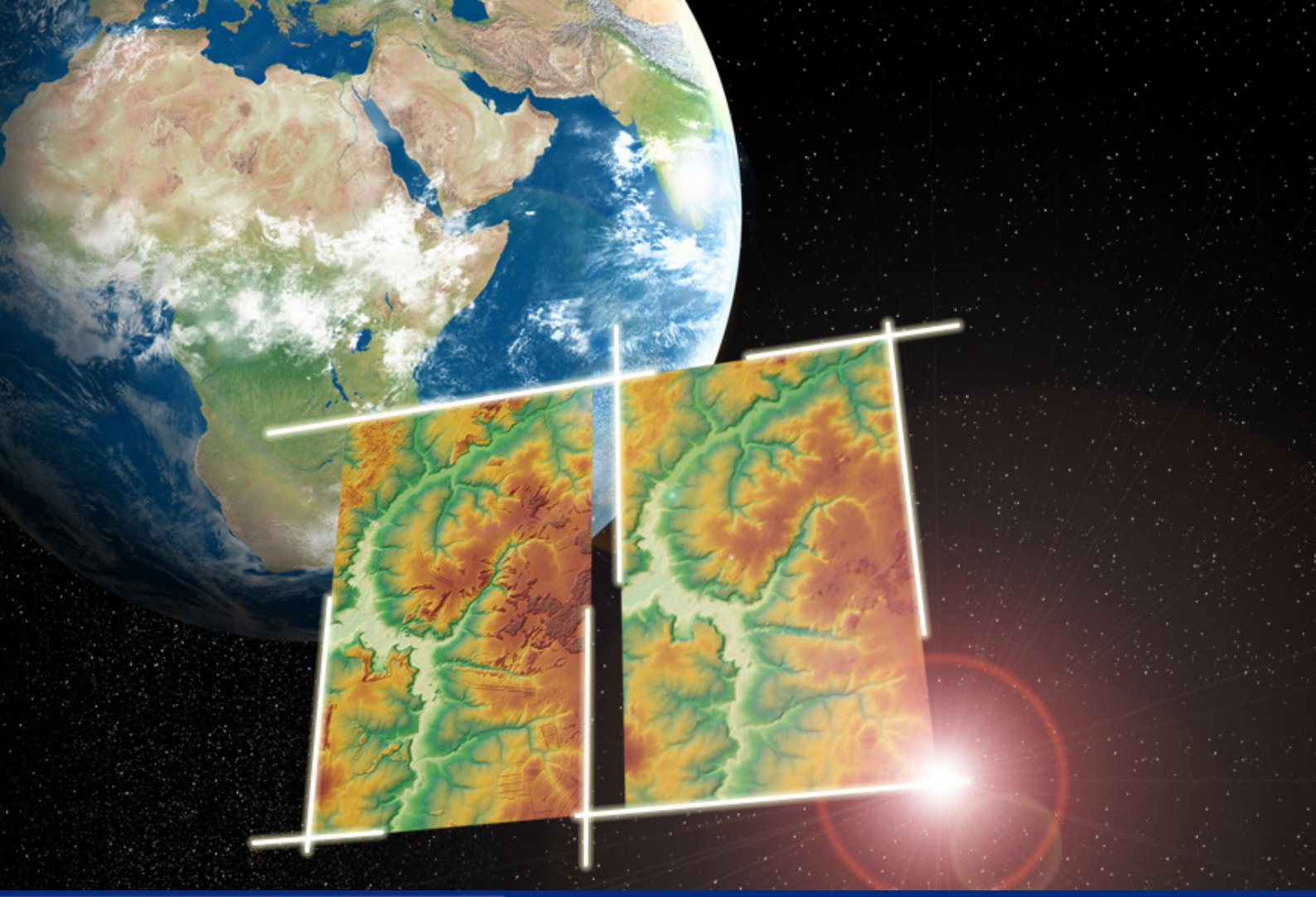

WorldDEM™ Technical Product Specification

Digital Surface Model, Digital Terrain Model

Version 2.5

Airbus Defence and Space
Intelligence

AIRBUS

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Abbreviations

Abbreviation	Description
AM2	Amplitude Mosaic (min. value)
AMP	Amplitude Mosaic (mean value)
AoI	Area of Interest
CE90	Circular error (90% confidence level)
COM	Consistency Mask
COV	Coverage Map
css	Cascading Style Sheets
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
DSM	Digital Surface Model
DTM	Digital Terrain Model
EDM	Editing Mask
EGM2008	Earth Gravitational Model 2008
EULA	End-User License Agreement
FLM	Filling Mask
GeoTIFF	Tag Image File Format - geocoded
HEM	Height Error Map
HRE	High Resolution Elevation
HREGP	High Resolution Elevation - Geographic Projection
InSAR	Interferometric Synthetic Aperture Radar
ICESat	Ice, Cloud and Elevation Satellite
ISO	International Organisation for Standardisation
jpg	Joint Photographic Experts Group (JPEG)
kml	Keyhole Mark-up Language
LE90	Linear Error (90% confidence level)
LSM	Layover - Shadow Mask
MMU	Minimum Mapping Unit
NGA	National Geospatial Intelligence Agency
pdf	Portable Document Format
png	Portable Network Graphics (image format)

Abbreviations	Description
QA	Quality Assurance
QC	Quality Control
RLM	Reliability Mask
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SRC	Source Mask
WAM	Water Indication Mask
WBM	Waterbody Mask
WGS84- G1150	World Geodetic System1984
xls	Microsoft Excel Spreadsheet
XML	eXtensible Markup Language

References

The following Reference Documents can be provided on request:

RD-01 DLR Document: TD-GS-PS-0021; DEM Products Specification Document, Version 3.1, 05.08.2016

RD-02 NGA STANDARDIZATION DOCUMENT: Implementation Profile for High Resolution Elevation (HRE) Products Specification of the data content, structure and metadata for raster elevation data products (2009-10-23) Version 1.0 NGA.IP.0002_1.0 2009-10-23

1 Introduction

WorldDEM™ is a Digital Elevation Model offered by Airbus Defence and Space that covers the entire land surface of the Earth (148.5 million km²). It is the most homogenous and accurate elevation model ever produced on a global scale. Currently available global DEMs are either not completely global, or suffer from severe artefacts and inaccuracies that render them unreliable in many locations.

WorldDEM™ is part of Airbus Defence and Space's Elevation Product Portfolio.

1.1 WorldDEM™ Data Basis

The WorldDEM™ products are based on the radar satellite data acquired during the TanDEM-X Mission, which is funded by a Public Private Partnership between the German State, represented by the German Aerospace Centre (DLR) and Airbus Defence and Space. The operation of the satellites in orbit, the data acquisition as well as the interferometric processing of the data is performed by DLR. Airbus Defence and Space is refining the processed data and is responsible for the commercialisation of the WorldDEM™ data.

The primary goal of the mission was the generation of a worldwide, consistent, and high precision Digital Surface Model (DSM) based on SAR interferometry. The two satellites TerraSAR-X and TanDEM-X operated as a single-pass SAR interferometer (InSAR), using the bi-static InSAR StripMap mode. At least two complete data coverages of the Earth's surface were acquired to generate the DEM product.

The data acquisition started in January 2011 and was completed by mid-2015.

1.2 Scope

This document describes the specification and format of the WorldDEM™ product portfolio. It provides a description of the post-processing (editing) process, the characteristics of the Digital Elevation Models and the ancillary data that are collected and/or generated during the data finishing process as well as the delivery formats.

2 WorldDEM™ Product Basics

The WorldDEM™ products are based on the "TanDEM-X Final DEM" produced by the DLR (RD-01). All post-processing procedures are performed by Airbus Defence and Space.

2.1 Definition and Specification

The WorldDEM™ product portfolio includes three products, which are based on each other (Figure 2-1) differing with respect to their level of editing (Table 2-1).

Figure 2-1: WorldDEM™ Product Portfolio

Table 2-1: WorldDEM™ Product Portfolio

Product	Description
$WorldDEM_{core}$	This Digital Surface Model (DSM) represents the surface of the Earth including buildings, infrastructure and vegetation. This unedited DSM is output of the interferometric processing without any refinement (editing). This product usually contains radar specific artefacts, voids and can include processing artefacts.
WorldDEM™	This product is a refined DSM ensuring hydrological consistency, i.e. flattening of water bodies and consistent flow of rivers, and includes editing of shore- and coastlines.
WorldDEM DTM	Digital Terrain Model (DTM) representing bare Earth terrain without obstruction features above ground.

The specifications described in this chapter are applicable to all WorldDEM™ products.

2.1.1 Accuracy

The level of resolution of an Elevation Model is very often described with respect to the High Resolution Elevation (HRE) products specification, published by the National Geospatial-Intelligence Agency (NGA) (RD-02). According to this specification, the WorldDEM™ products are comparable to HREGP standard (HRE Level 1). GP stands for "Geographic Projection".

The accuracy is specified as *absolute* and *relative* accuracy.

Absolute accuracy values describe all random or systematic uncertainties of a pixel, in horizontal or vertical direction, with respect to the horizontal or vertical datum used. The errors are expressed as linear or circular error at a 90 percent confidence level and are based on the global product (97% of global landmass).

The **relative accuracy** describes the consistency of the digital elevation modelling. The relative accuracy is specified as uncertainty between two DEM pixels caused by random errors. The relative uncertainty is expressed as linear or circular error at a 90 percent confidence level.

Due to the global coverage of the WorldDEM, all accuracy statistics and values stated in this document are calculated as an arithmetic mean on global level. Local deviations occur.

2.1.2 Quality Control

The data sets provided are checked for technical, statistical and visual consistency. The applied quality control steps comprise of the check for data set completeness, the technical specification of the product content, overall statistical plausibility, as well as overall visual plausibility.

2.1.3 Pixel Spacing

The grid spacing of the WorldDEM™ products is 0.4 arc seconds in latitude, which equals approximately 12m (exactly 12.37m at the equator and 12.33m near the poles). In longitude, the pixel spacing depends on the latitude, as listed in Table 2-2.

Table 2-2: Pixel Spacing Depending on Latitude

Zone	Latitude Band	Latitude Pixel Spacing	Longitude Pixel Spacing
I	0° - 50° North/South	0.4”	0.4”
II	50° - 60° North/South		0.6”
III	60° - 70° North/South		0.8”
IV	70° - 80° North/South		1.2”
V	80° - 85° North/South		2.0”
VI	85° - 90° North/South		4.0”

These pixel spacing changes in longitude at the border of two zones affect the number of pixels in longitudinal and result in a kind of pixel shift as depicted in Figure 2-2.

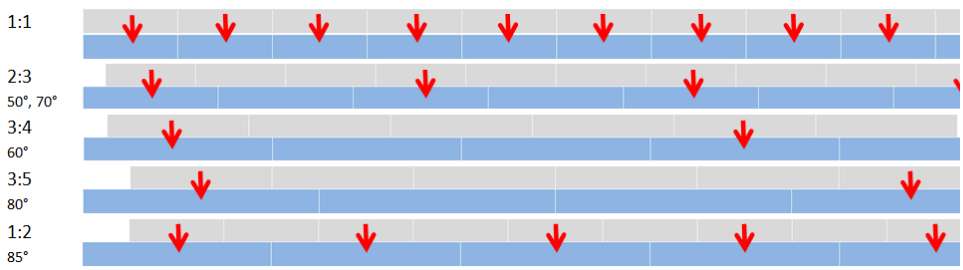

Figure 2-2: Longitudinal Pixel Spacing at the Border of Two Zones

2.1.4 Format

The WorldDEM™ products are available as 32-bit floating data in GeoTIFF format. A NoData value (-32767.0) is used for points where the elevation information could not be determined. The vertical unit for measurement of elevation height is meters.

2.1.5 Projection

The WorldDEM™ products are available in Geographic Coordinates; the horizontal reference datum is the World Geodetic System 1984 (WGS84-G1150) and the vertical reference datum is the Earth Gravitational Model 2008 (EGM2008).

2.1.6 Coverage

The whole landmass of the Earth is covered. Some small islands (e.g. atolls) might not be represented accurately. For clarification: The North Pole is not part of the product, as there is no land mass present.

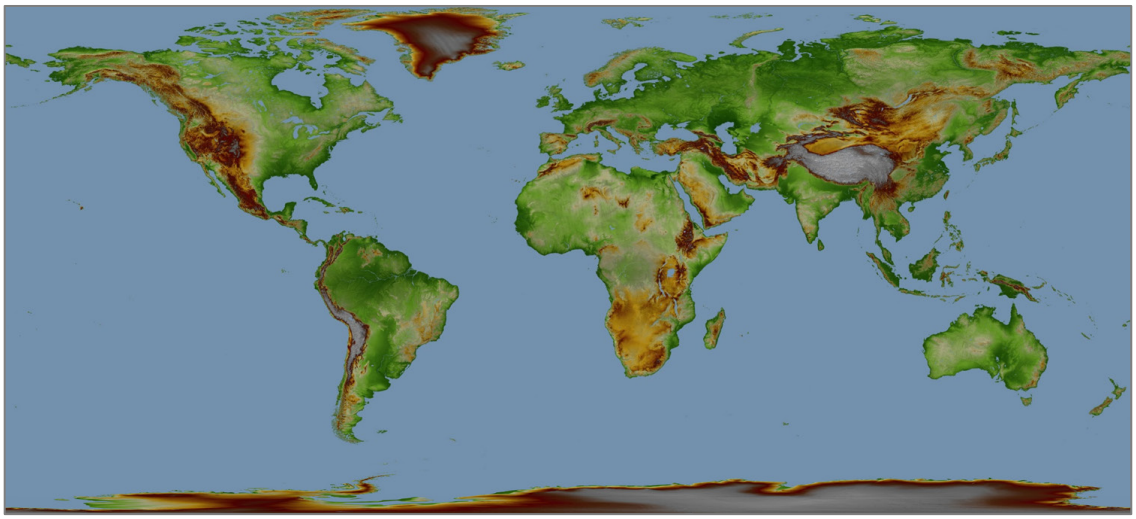

Figure 2-3: WorldDEM Global Coverage

2.1.7 Product Delivery

Depending on the size of the AoI, WorldDEM™ products are delivered in one file covering the complete AoI or in several files. Maximum tile size is up to 50,000 km² (below 85° North and South).

An AoI covering several geocells will be delivered in geocell units. AoIs covering parts of different pixel spacing zones (as described in Chapter 2.1.3) will be split at the zone border, independent of the overall AoI size.

When an AoI is delivered in tiles it is ensured that the tiles have an overlap of one pixel row and one pixel column to the adjacent tile.

2.1.8 Summary

Table 2-3: Overview of Product Definition

Specification Parameter		Value
File Format		GeoTIFF
Data Type		32 Bit, floating
NoData Value		-32767.0
Projection		Geographic Coordinates
Coordinate Reference System	Horizontal	WGS84-G1150
	Vertical	EGM2008
Pixel Spacing		0.4 arcsec (approx. 12m)*
Vertical Unit		Meter

*see Table 2-2

2.2 Impacts of SAR Specific Characteristics

Due to the acquisition geometry and radar characteristics, relief-dependent effects such as layover, foreshortening or shadow may appear in the data used for generating the raw DSM. Particularly in dense urban and mountainous areas as well as at forest edges, such effects can result in less accurate and occasionally invalid elevation information in affected areas. In the unedited DSM data, these areas are represented as voids or artefacts. In edited WorldDEM™ products, these effects will be eliminated as far as possible. In areas with no data, editing (interpolation for example) may be applied to close small gaps in the data. In larger areas with no data, a secondary DEM may be used to fill in a void, to ensure product continuity. In all cases where data is interpolated or filled in, this information is recorded.

Since the WorldDEM™ data was collected in several coverages, over a period of several years, there are areas that are subject to the temporal or seasonal changes which occurred between the acquisitions. An example of this would be a forest that was cut down between two coverages: The elevation in the first coverage would be the top of the trees, but in the second coverage the elevation would be the ground on which the trees were formerly growing. The interferometric data processor is designed to deal with such situations and should resolve a correct surface elevation (before or after tree cutting) in most cases. In rare cases where the processor cannot resolve a true elevation, manual editing may be applied to the DSM to correct the improbable elevation. This situation applies to any part of the Earth's surface that might change during the four years of data collection, such as new buildings, surface mining areas, road construction, shrinking glaciers, etc.

Due to variations in weather and climate during data acquisition, the elevation measurements on snow covered areas, ice-sheets or glaciers may not fall within the standard specifications of the WorldDEM™ product. Similarly, seasonal changes in water bodies (freezing and thawing, high and low water) may occur between the data

acquisitions. During the editing of WorldDEM™ products, these seasonal changes are taken into account. Water is edited using the greatest extent (high water mark) of the water. In rare cases, some water bodies, such as very large lakes, may be set to more than one elevation, due to water surface elevation differences during data acquisition. In general, lakes that are frozen in all coverages are left unedited in the WorldDEM™ as usually their elevations are already correctly portrayed. Infrequently, it may happen that the surface of the frozen lake is arched upward and the elevation is higher than the shoreline.

The quality of the height estimation also depends on the surface type and capability of the signal to penetrate into the surface. In vegetated areas and especially in forests the penetration depth is related to the vertical distribution of the scatterers within the canopy and their dielectric properties. In other words, the location of the scattering phase center and corresponding height measurement is related to the vertical structure of the forest (height, density, tree type composition) apart from imaging parameters. This needs to be kept in mind when WorldDEM™ is used for forest canopy height estimation. One could assume that due the penetration of the signal into the forest volume, the forest height is underestimated to a varying extent depending on forest structure characteristics.

3 WorldDEM$_{core}$ Product

The WorldDEM$_{core}$ is a package consisting of unedited Digital Surface Model data, auxiliary data and metadata.

3.1 Definition and Specification

The WorldDEM$_{core}$ product is a Digital Surface Model based on the output DEM of the TanDEM-X Mission (s. RD-01). After passing the Income-Quality-Check procedure the data is transformed from ellipsoid heights (WGS84-G1150) to geoidal heights (EGM2008).

Apart from the transformation to geoidal heights, no further editing is applied to the WorldDEM$_{core}$. Therefore all SAR specific artefacts in the terrain or over water, such as voids or spikes and wells, remain in the WorldDEM$_{core}$ data. In addition, all processing artefacts, e.g. non-identical pixels in the overlap area of two geocell borders, remain unchanged.

The specification described in Chapter 2.1 is valid for WorldDEM$_{core}$ and summarised together with the accuracy of the product in Table 3-1.

Table 3-1: WorldDEM$_{core}$ - Specification

Specification Parameter		Value
File Format		GeoTIFF
Data Type		32 Bit, floating
NoData Value		-32767.0
Projection		Geographic Coordinates
Coordinate Reference System	Horizontal	WGS84-G1150
	Vertical	EGM2008
Pixel Spacing		0.4 arcsec (approx.12m) *)
Vertical Unit		Meter
Absolute Vertical Accuracy **) ***) ****)		< 4m (90% linear error)
Relative Vertical Accuracy ***) ****)		< 2m (slope ≤20%) < 4m (slope > 20%) (90% linear point-to-point error within an area of 1° x 1°)
Absolute Horizontal Accuracy **) ***) ****)		< 6m (90% circular error)

*) See Table 2-2
**) Based on validation results using ICESat GLAS reference points (TanDEM-X Mission Goal: < 10m)
***) Excluding Antarctica and Greenland (physical reflection properties differ between WorldDEM and reference data in regions with permanent snow/ice cover)
****) Due to the global coverage of the WorldDEM, all accuracy statistics and values stated in this document are calculated as an arithmetic mean on global level. Local deviations occur.

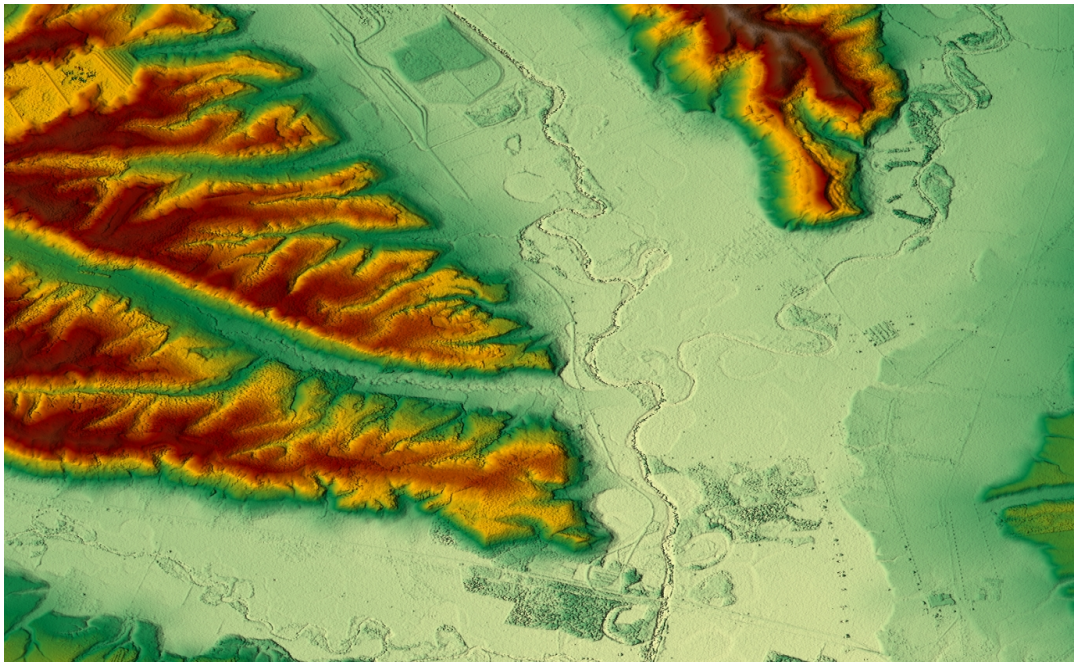

Figure 3-1: WorldDEM$_{core}$

3.2 Auxiliary Layer

The WorldDEM$_{core}$ package contains several auxiliary information layers, which were generated during the production process. These are raster datasets in GeoTIFF format (s. Table 3-2).

Table 3-2: WorldDEM$_{core}$ - Auxiliary Layers

Auxiliary Layer		Data Format
Amplitude Mosaic (mean value)*	AMP	16 bit unsigned integer, GeoTIFF
Amplitude Mosaic (min. value) *	AM2	16 bit unsigned integer, GeoTIFF
Consistency Mask*	COM	8 bit unsigned integer, GeoTIFF
Coverage Map*	COV	8 bit unsigned integer, GeoTIFF
Height Error Map*	HEM	32 bit floating point, GeoTIFF
Layover/Shadow Mask*	LSM	8 bit unsigned integer, GeoTIFF
Water Indication Mask*	WAM	8 bit unsigned integer, GeoTIFF
Reliability Mask	RLM	8 bit unsigned integer, GeoTIFF

* s. RD-01

Amplitude Mosaic (AMP, AM2)

There are two amplitude mosaic layers (radar images), which consist of the mosaic of the calibrated amplitude values of all contributing DEM scenes:

- Amplitude Mosaic (AMP) represents the mean calibrated amplitude values
- Amplitude Mosaic (AM2) represents the minimum calibrated amplitude values

Both image layers are made available for further DEM product value-adding, e.g. water body detection and editing.

Consistency Mask (COM)

The Consistency Mask shows DEM pixels which have height inconsistencies between the different DEM acquisitions.

This mask includes two kinds of inconsistencies:

- Large absolute height differences, e.g. due to phase unwrapping errors of incoherent areas like water bodies, shadow, layover.
- Small absolute height differences exceeding the corresponding height errors, e.g. due to temporal changes.

Table 3-3 shows the meaning of the pixel values in the consistency mask.

Table 3-3: Consistency Mask

Pixel Value	Meaning
0	Invalid / no data
1	Larger inconsistency
2	Smaller inconsistency
4	Only one coverage
8	All heights are consistent (at least one consistent height pair)
9	Larger inconsistency but at least one consistent data pair
10	Smaller inconsistency but at least one consistent data pair

Coverage Map (COV)

The Coverage Mask indicates how many height values from different DEM acquisitions were available for mosaicking.

Pixel values correspond to the number of DEM contributed to the final DEM value (1 = 1 coverage, 2 = 2 coverages etc.) while “0” means “no data”.

Height Error Map (HEM)

The Height Error Map represents the corresponding height error for each DEM pixel in the form of the standard deviation derived from the interferometric coherence and

geometrical consideration. It represents errors in the interferometric phase determination and the combination of different coverages (RD-01). These are random errors and do not include any kind of systematic errors, such as elevation offsets related to erroneous orbital parameters. Phase unwrapping errors are not represented here.

The pixel values in the Height Error Map are standard deviation values in meters. Invalid or missing data are set to -32767.0.

Layover and Shadow Mask (LSM)

The Layover and Shadow Mask provides an indication, where layover and shadow areas are expected in the DEM data. This information is based on SRTM-C and Globe DEM, with respect to the TerraSAR-X / TanDEM-X sensor geometry of each individual DEM scene (see Table 3-4).

Table 3-4: Layover and Shadow Mask

Pixel Value	Meaning
0	Invalid / no data
1	Valid DEM value
3	Shadow
5	Layover
7	Shadow and Layover

Water Indication Mask (WAM)

During the DEM processing, potential water bodies are identified based on the fact that water is generally incoherent in the data and yields noise-only values, which are not related to any height measurement (RD-01).

The identification is a fully automated process. To reduce misclassifications the external sources MODIS and SRTM are used for pre-classification.

The following areas are excluded from water body detection:

- Areas identified as “dry” in MODIS and SRTM data (MODIS: snow, ice, arid areas)
- Areas with slopes steeper than 20° (based on SRTM)
- Layover and shadow areas (LSM, SRTM)

Overall, the Water Indication Mask indicates the number of occurrences of extracted water pixels found (see Table 3-5). The higher the pixel value the higher is the reliability of the water indication. To have a maximum extent of the class “water”, the pixel values from 3 to 127 can be selected.

Islands smaller than 1ha (100m x 100m) and water bodies smaller than 2ha (200m x 100m) are not considered in the Water Indication Mask.

The Water Indication Mask indicates the number of occurrences of extracted water pixels found by three extraction methods (RD-01):

1. With a strict beta nought threshold on the amplitude (strict AMP Thresh1, of -18 dB)
2. With a more relaxed beta nought threshold on the amplitude (relaxed AMP Thresh2, of -15 dB)
3. With a threshold based on the coherence (COH Thresh) of COH Thresh < 0.23.

*Note: Water body extents and lake/river/ocean heights are **not** edited in WorldDEM$_{core}$.*

Table 3-5: Water Indication Mask

Pixel Value	Meaning
0	Invalid / no data
1	Valid DEM value
3	1 x water detected with *relaxed* AMP-Thresh2
5	2 x water detected with *relaxed* AMP-Thresh2
7	3 or more times water detected with *relaxed* AMP-Thresh2
9	1 x water detected with *strict* AMP-Thresh 1
17	2 x water detected with *strict* AMP-Thresh 1
25	3 or more times water detected with *strict* AMP-Thresh1
33	1 x water detected with COH-Thresh
65	2 x water detected with COH-Thresh
97	3 or more times water detected with COH-Thresh
129	Water body detection is not performed according to MODIS classes or SRTM

The given values are summarised in case of a parallel presence of one of the options given for AMP-Thres1, AMP-Thres 2 or COH-Thres.

Reliability Mask (RLM)

The Reliability Masks indicates the reliability of each DEM pixel value generated by taking into account the DEM, HEM and COM information. The mask provides 2 types of information.

1. Indication of areas with a very low point-to-point accuracy by a range of values (1-127)
2. Flag of areas with COM = 1 with the parallel indication of areas with low point-to-point accuracy (129-255)

Areas with no valid height information are represented by the value 0.

4 WorldDEM™ Product

For a continuous and accurate representation of the Earth's surface elevation, the editing of the $WorldDEM_{core}$ is required. The WorldDEM™ is a package consisting of edited Digital Surface Model (DSM), quality layers (optional) and metadata.

4.1 Definition and Specification

The WorldDEM™ product is an edited DSM produced based on the $WorldDEM_{core}$ product. The editing of $WorldDEM_{core}$ is necessary to reduce impacts of certain SAR-specific data features and artefacts in the elevation model.

The specification described in Chapter 2.1 is valid for WorldDEM™ and is summarised together with the accuracy of the product in Table 4-1.

Table 4-1: WorldDEM™ Specification

Specification Parameter		Value
File Format		GeoTIFF
Data Type		32 Bit, floating
NoData Value		-32767.0
Projection		Geographic coordinates
Coordinate Reference System	**Horizontal**	WGS84-G1150
	Vertical	EGM2008
Pixel Spacing		0.4 arcsec (approx. 12m) *)
Vertical Unit		Meter
Absolute Vertical Accuracy **) ***) ****)		< 4m (90% linear error)
Relative Vertical Accuracy ***) ****)		< 2m (slope ≤20%) < 4m (slope > 20%) (90% linear point-to-point error within an area of 1° x 1°)
Absolute Horizontal Accuracy **) ***) ****)		< 6m (90% circular error)

*) See Table 2-2
**) Based on validation results using ICESat GLAS reference points (TanDEM-X Mission Goal: < 10m)
***) Excluding Antarctica and Greenland (physical reflection properties differ between WorldDEM and reference data in regions with permanent snow/ice cover)
****) Due to the global coverage of the WorldDEM, all accuracy statistics and values stated in this document are calculated as an arithmetic mean on global level. Local deviations occur.

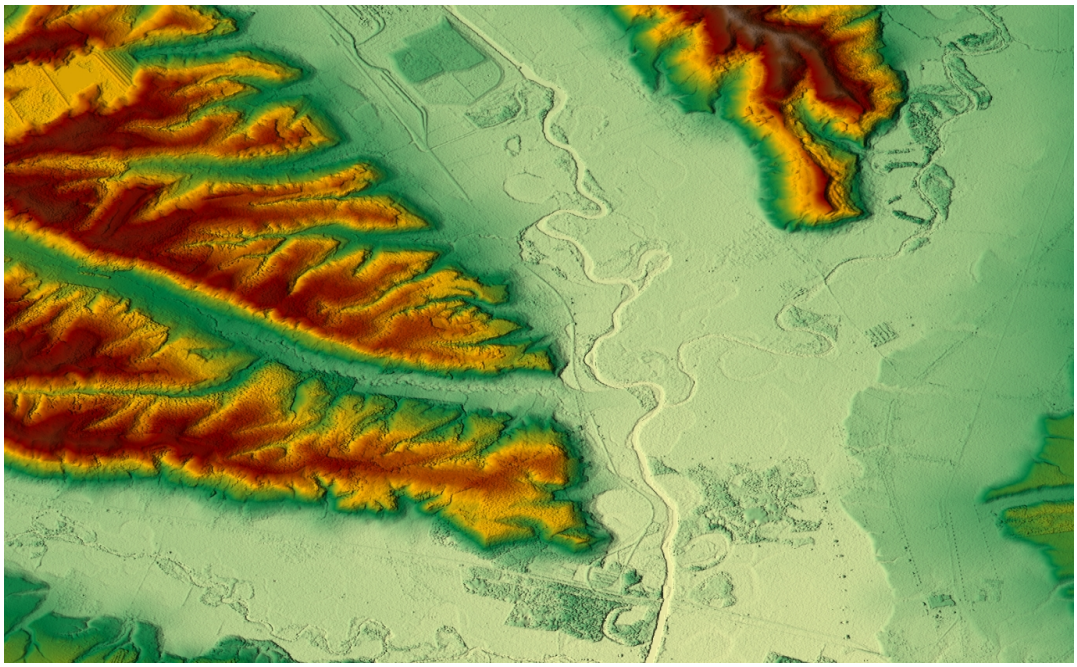

Figure 4-1: WorldDEM™

4.2 Editing Process

The WorldDEM™ editing process is performed in two major steps:

In a first editing step implausible terrain features (e.g. artefacts caused by layover and shadow) are identified and edited. The identification and editing of implausible terrain features is a highly automated process; however some manual user interaction is required to prove and ensure the quality of the results.

The $\text{WorldDEM}_{\text{core}}$ does not represent plausible elevations over most water surfaces. Therefore, the editing of water bodies is the second processing step required to produce a high quality elevation model. This editing step comprises the extraction and editing of water body features according to the WorldDEM™ editing specifications. The identification of water bodies is done based on the respective Amplitude Mosaic image data. Since water tends to have a very dark appearance in the image, this data is in many cases a reliable source for the detection of water bodies.

The terrain and hydro editing process is followed by a Quality Control (QC). This QC check consists of a combination of automatic tools and visual inspection of the data by an independent operator. For example, QC tools automatically detect if voids are left in the edited product, if water body features fulfil their required minimum mapping unit (MMU) etc. A QC operator visually checks if features are missing or are over-classified, and if the editing were applied correctly. This check is a thematic validation and is performed according to ISO 2859.

4.2.1 Terrain Editing

The terrain editing step comprises the correction of terrain artefacts caused by SAR specific characteristics or the DSM processing. Based on the surface characteristic and the information of existing auxiliary layers these artefacts can easily be identified and edited.

Main terrain editing steps are the removal of spikes and wells, the interpolation or filling of voids and the editing of heavy noise. In addition, implausible negative elevations nearby ocean shorelines are raised.

Spike / Well Removal

Single pixels with a significant height difference of 20 or more meters difference to the surrounding 8 pixels are defined as spikes or wells. Spikes and wells can be automatically detected and removed. The removal of these artefacts is based on an interpolation of the respective pixel to the average elevation of its eight neighbours.

Void Filling

Voids are represented by a no-data value (-32767.0) in the elevation model. Single pixel voids, or voids of a few pixels (up to 16 pixels) are automatically identified and interpolated. This interpolation takes the values of adjoining valid pixels and calculates the missing elevations information based on these.

Larger void areas (larger than 16 pixels) are filled with available ancillary DEM data. Based on the Delta Surface Filling Method, alternate sources of elevation are used to fill voids. Any available sources of DEM data can be used as a source data for void filling: The selection of infilling datasets is based on their availability and quality.

Editing of Noise

Shadow areas, forest decorrelation and very smooth surfaces (e.g. water, sand) can lead to noise in the DSM. Strong noise, that can be automatically detected, is either smoothed or interpolated to raise the plausibility of the DSM characteristic. Large areas are replaced with ancillary DEM data.

Raising of Implausible Negative Elevations

In very moderate terrain nearby ocean shorelines (e.g. mudflats or beaches), some elevation pixels represent values below or equal to the ocean height. These pixels are automatically identified and raised so they represent an elevation value above 0m. Areas that are known as lower than the ocean elevation are not changed (e.g. parts of The Netherlands).

Table 4-2: Terrain Editing Specification

Feature	Definition	Editing Approach
Spikes/ Wells	20m minimum height difference of centre pixel compared to average elevation of its eight neighbours	Interpolation of centre pixel to average elevation of its 8 neighbours
Voids	Pixels with missing elevation information, represented by the value -32767.0	Voids ≤ 16 pixels Interpolation according to surrounding terrain
		Voids > 16 pixels Infill of alternate DEM data
Noise	Noise that can be automatically detected	Smoothing of noise by a boxcar or Gaussian blurring algorithm or infilling an alternate DSM source
Negative Elevation	Elevations ≤ 0m nearby ocean shoreline (except areas known to be below 0m)	Raising of unnatural negative elevations to positive elevations

4.2.2 Hydrology Editing

The editing of water bodies (hydro-enforcement) is an important processing step to achieve a high quality elevation model. In the WorldDEM_{core} water surfaces do not represent plausible elevations; this is corrected during the hydro editing process. The hydro editing process consists mainly of the extraction, classification and implementation of water body features according to the WorldDEM™ editing specification.

All features are extracted to their full extent (high water) using the Amplitude Mosaic image. Since water tends to have a very dark appearance in the image, this data is in many cases a reliable source for the detection of water bodies. The extraction of water bodies is always based on the incoming WorldDEM_{core} data package (Amplitude Mosaic, RLM, DSM).

The next production step comprises the separation of identified water into different water body classes. For the hydro editing of the WorldDEM™ data, three different types of water body features are defined:

- Ocean: Ocean water bodies are set to the elevation height of 0m, including all seas, inlets, fjords and any other extensions of the ocean.
- Lake: This feature class covers all standing inland water bodies (e.g. lakes, reservoirs, fishponds) that are represented by the presence of water in the Amplitude Mosaic image. Each lake feature is set to a single elevation.
- River: This feature class represents all Double Line Drain Features such as rivers and canals. Double Line Drains are features with a changing elevation which flows in one direction (monotonic).

Finally, all extracted and classified water features that are fulfilling the WorldDEM™ editing specification are edited. According to its feature type, a water body feature is “flattened” to a single elevation (ocean, lakes) or to monotonic flowing elevations (rivers). The water flattening process includes ensuring that the shoreline elevations of a water body are never below the elevation of the water surface.

Note:

- Non-permanent water-bearing rivers (wadis) or sporadically dry lakes are treated according to the water portrayal in the amplitude mosaic and the DSM. Frozen water is not considered as water and remains unedited.
- Permanent and non-permanent sea-ice will be edited as ocean. In the case of sea ice, the shoreline is subject to interpretation.
- Water surfaces not detectable as water in the used ancillary data (e.g. Amplitude Mosaic, RLM, DSM) due to their specific reflection characteristics are not considered as water and remain untreated.

Table 4-3 describes the detailed editing rules applied during the hydrological editing processes. Feature extraction and editing rules are based on minimum mapping units (MMU).

Table 4-3: Hydrological Editing Specification

Feature Class	Definition	Extraction Rule	Editing Rule
Oceans	Ocean water bodies that are represented by the presence of water in the Amplitude Mosaic image (high water)	All	All ocean features are set to 0m
Lakes	Standing inland water bodies (e.g. lakes, reservoirs, fishponds) that are represented by the presence of water in the Amplitude Mosaic image (high water)	Extract all lakes that are larger than 7000m² (Lake MMU ≥ 7000m²)	Lakes ≥ MMU are flattened to a single elevation value Lakes < MMU are not edited (maintained as land)
Rivers	Double Line Drain Features (river, canals) that are represented by the presence of water in the Amplitude Mosaic image (high water)	Start river extraction when it has a constant width of 50m over 500m Continue river extraction until it meets a lake or ocean or unless it disappears completely	Set river elevation monotonically in 0.5m steps
Islands	Islands that are represented by the presence of land in the Amplitude Mosaic image	Extract all islands that are larger than 1500m² (Island MMU ≥1500m²)	Islands ≥ MMU are maintained as land Islands < MMU are flattened appropriately as water
Shoreline Pixels	First row of shoreline pixels (all water body features)		Shoreline pixels below the adjacent water body elevation are raised to 0.5m above water body elevation
Bridges	Bridges over water body features	Bridges over water are classified appropriately as water	Bridges over water are flattened appropriately as water
	Bridges over land (e.g. causeways)	Bridges over land are maintained as land	Bridges over land are not edited (maintained as land)
Peninsulas & Coastal Features (Piers, Jetties)	Land inlets or coastal features (e.g. piers, jetties) that are represented by the presence of land in the Amplitude Mosaic image	All features wider than 40m are extracted as land (MMU ≥ 40m)	Features ≥ MMU are maintained as land Features < MMU are flattened appropriately as water
Water Inlets	Water inlets that are represented by the presence of water in the Amplitude Mosaic image	All features wider than 40m are extracted as water (MMU ≥ 40m)	Features ≥ MMU are flattened appropriately as water Features < MMU are maintained as land
Ships, Boats, Ocean Platforms etc.	Temporary or floating features	All features are extracted as water	All feature are flattened appropriately as water

4.2.3 Additional Editing - Airports

Due to their smooth surface, airport runways and other large paved areas frequently reflect radar waves away from the radar sensor similar to water bodies, and this results in poor DSM data quality. Therefore, paved runway, taxiway and apron surfaces of large airports are flattened to a consistent elevation, based on the adjacent elevations during the editing process. Slopes on airfields are stepped.

The edited airports are flagged in the Editing Mask (EDM).

Table 4-4: Airport Editing Specification

Feature	Definition	Editing Rule
Airports	Paved surface of airports (incl. runways, taxiways and aprons)	Paved areas are set to a consistent elevation and / or stepped where necessary

4.3 Quality Layers

Quality Layers can be optionally ordered with the WorldDEM™ product. Several auxiliary information layers are generated during the production process and are available as raster data in GeoTIFF format (Table 4-5).

Table 4-5: WorldDEM™ - Quality Layers

Quality Layer		Data Format
Amplitude Mosaic (mean value)*	AMP	16 bit unsigned integer, GeoTIFF
Filling Mask	FLM	8 bit unsigned integer, GeoTIFF
Editing Mask	EDM	8 bit unsigned integer, GeoTIFF
Water Body Mask	WBM	8 bit unsigned integer, GeoTIFF

* s. RD-01

Amplitude Mosaic (AMP)

The Amplitude Mosaic (mean value), the radar image, consists of the mosaic of the mean calibrated amplitude values of all contributing DEM scenes (at least 2 scenes, up to 10 scenes).

Filling Mask (FLM)

This Filling Mask is created during the WorldDEM™ terrain editing process (Chapter 4.2.1). It includes all information of the terrain editing process. All edited and filled pixels are flagged in this mask. Table 4-6 shows the meaning of the pixel values of the Filling Mask.

Table 4-6: Filling Mask - Pixel Values

Pixel Value	Meaning
0	Void (no data)
1	Edited (except filled pixels)
2	Not edited / not filled
3	ASTER[1]
4	SRTM90[2]
5	SRTM30[2]
6	GMTED2010[3]
7	SRTM30plus[4]
8	TerraSAR-X Radargrammetric DEM
9	AW3D30[5]
..	*fill source*
..	*fill source*

Editing Mask (EDM)

The Editing Mask summarises all changes applied to the DEM pixels. This mask indicates all DEM pixels that were modified during the terrain and hydro editing process. The final Editing Mask represents the last editing process that was applied to a pixel.

Table 4-7 shows the meaning of the pixel values.

Data resources used to enhance licensed data material (void filling):

[1] ASTER Global Digital Elevation Map retrieved from https://asterweb.jpl.nasa.gov/gdem.asp, NASA/METI/AIST/Japan Space Systems, and U.S./Japan ASTER Science Team

[2] STRM Digital Elevation Data retrieved from http://earthexplorer.usgs.gov/ and from http://srtm.csi.cgiar.org/ U.S. Geological Survey, https://lta.cr.usgs.gov/sites/default/files/Data%20Citation_1.pdf

[3] GMTED2010 Elevation Data retrieved from http://earthexplorer.usgs.gov/ produced by the U.S. Geological Survey, https://lta.cr.usgs.gov/sites/default/files/Data%20Citation_1.pdf

[4] NASA LP DAAC, 2013, NASA Shuttle Radar Topography Mission Global 1 arc second, Version 3.0. NASA EOSDIS Land Processes DAAC, 2013 USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov), accessed May 2nd 2017 at https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL1.003.

[5] ALOS World 3D-30m (AW3D30) provided by Japan Aerospace Exploration Agency (JAXA)

Table 4-7: Editing Mask - Pixel Values

Pixel Value	Meaning
0	Void (no data)
1	Not edited
2	Infill of external elevation data
3	Interpolated pixels
4	Smoothed pixels
5	Airport editing
6	Raise of negative elevation pixels
7	Flattened pixels
8	Ocean pixels
9	Lake pixels
10	River pixels
11	Shoreline pixels
12	Morphed pixels (series of pixels manually set)
13	Shifted pixels

Water Body Mask (WBM)

The Water Body Mask shows all DEM pixels, which are classified as water and edited according to the categories Ocean, Lake or River. Table 4-8 shows the meaning of the pixel values.

Table 4-8: Water Body Mask - Pixel Values

Pixel Value	Meaning
0	No water
1	Ocean
2	Lake
3	River

5 WorldDEM DTM Product

The WorldDEM DTM product is a Digital Terrain Model (DTM) representing a bare Earth surface. The WorldDEM DTM is a package consisting of Digital Terrain Model data, quality layers (optional) and metadata.

5.1 Definition and Specification

The generation of the DTM is based on the WorldDEM™ product, its Water Body Mask (see Chapter 4) as well as the Auxiliary Layers of $WorldDEM_{core}$ (see Chapter 3.2).

WorldDEM DTM represents bare Earth elevation information, without obstruction features above ground (Surface Features). However, terrain characteristics (Terrain Features) are preserved.

In the WorldDEM DTM editing process, the following **Surface Features** are removed:

- Built-up Areas
  - Single buildings or spatial agglomeration of buildings and man-made features, e.g. apartments, commercial buildings, industrial installations, railway stations, gas stations
- Vegetation
  - Spatially closed canopy areas:
    - Forest
    - Agriculture areas (e.g. palm tree plantations, fruit tree plantations) and cropland (e.g. hops, corn)
  - Rows and small agglomerations of trees, hedges or single trees

The following **Terrain Features** are key elements of the land characteristics and are preserved as far as possible during the DTM generation process:

- Ridge and Depth Lines
  - Distinct vertical interruptions in the slope of the Earth surface, e.g. mountain crest, glacier crest, tectonic reverse faults, narrow valleys
- Break Lines
  - Distinct horizontal interruption in the slope of the Earth surface, e.g. edge of deeply incised stream beds, plateau and terrace edges, crater rims, open mine pits
- Hydrological Barrier features enclosing or retaining water on the Earth surface with significant influence on the hydrologic characteristic of the DTM:
  - Dams, levees, dikes, embankments, causeways

The specification described in Chapter 2.1 is valid for WorldDEM DTM and is summarised together with the accuracy of the product in Table 5-1.

Table 5-1: WorldDEM DTM Specification

Specification Parameter		Value
File Format		GeoTIFF
Data Type		32 Bit, floating
NoData Value		-32767.0
Projection		Geographic Coordinates
Coordinate Reference System	**Horizontal**	WGS84-G1150
	Vertical	EGM2008
Pixel Spacing		0.4 arcsec (approx. 12m) *)
Vertical Unit		Meter
Absolute Vertical Accuracy **) ***) ****)		< 4m (90% linear error)
Relative Vertical Accuracy **) ***) ****)		< 2m (slope ≤20%) < 4m (slope > 20%) (90% linear point-to-point error within an area of 1° x 1°)
Absolute Horizontal Accuracy **) ***) ****)		< 6m (90% circular error)

*) See Table 2-2
**) Based on validation results using ICESat GLAS reference points (TanDEM-X Mission Goal: < 10m)
***) Excluding Antarctica and Greenland (physical reflection properties differ between WorldDEM and reference data in regions with permanent snow/ice cover)
****) Due to the global coverage of the WorldDEM, all accuracy statistics and values stated in this document are calculated as an arithmetic mean on global level. Local deviations occur.

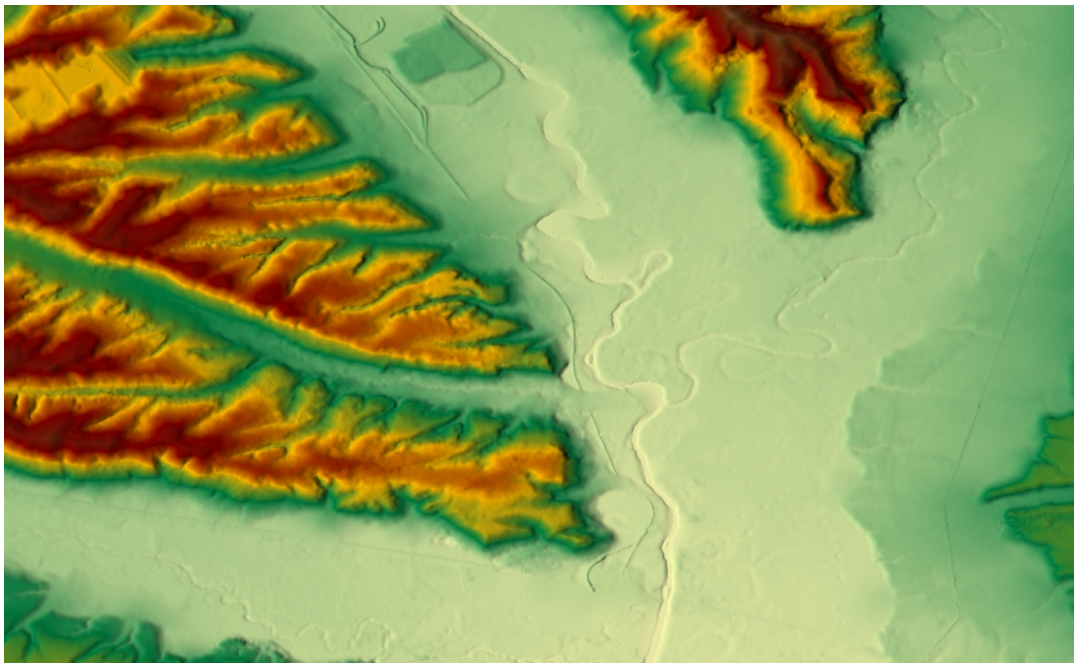

Figure 5-1: WorldDEM DTM

5.2 Editing Process

The WorldDEM DTM generation is performed with the following processing steps:

- In a fully automated step, the terrain characteristics and surface features are delineated, segmented and analysed. The delineation of non-ground surface objects (such as vegetation features and artificial objects) is split into two groups:
  - Objects exceeding a certain extent so that they are handled as standalone object (e.g. forest)
  - Group of objects that are too small to be captured independently (e.g. bush land or buildings)
- Generalisation and classification of all segmented non-ground surface objects is performed in a semi-automated manner, depending on the radar reflection characteristics (signal intensity & signal quality). These are then clustered into three different classes that undergo different height removal procedures during later DTM elevation processing. Depending on the characteristics and extent of objects they will be shifted (subtracted from the DSM), filtered or interpolated. Areas of ground truth remain untouched as these already have a proper terrain elevation. A manual check is performed to verify the results of the automated classification.
- The height of identified non-surface objects is estimated when the objects are classified as standalone objects. In an automated process, bare Earth elevation next to the object is considered in the determination of the object height.
- The non-ground objects are removed from the DSM according to their segment classification:
  - Subtraction of measured height of “standalone” objects
  - Filtering or interpolation of object heights in case objects are too small to be captured independently (e.g. single trees and houses). The height values surrounding local maxima are used to remove each object.
- After the object height removal a homogenization of the areas is performed. In a semi-automated process adapted filtering is applied depending on location taking into account the terrain and surface characteristics. Break lines, ridge and depth lines are detected and preserved together with hydrologically relevant areas from the Water Body Mask (WBM) during this homogenization process.
- The quality of the WorldDEM DTM is ensured through the following major control steps:
  - Calculation of a difference layer between DSM and DTM: DTM elevations above the DSM will be validated and potentially reprocessed.
  - Quality check on hydrological consistency

Finally, a grid-based visual inspection is performed.

5.3 Quality Layers

Quality Layers can be optionally ordered with the WorldDEM DTM product. Auxiliary information is generated during the production process and is available as raster data in GeoTIFF format (Table 5-2).

Table 5-2: WorldDEM DTM - Quality Layers

Quality Layer		Data Format
Amplitude Mosaic (mean value)*	AMP	16 bit unsigned integer, GeoTIFF
Filling Mask	FLM	8 bit unsigned integer, GeoTIFF
Water Body Mask	WBM	8 bit unsigned integer, GeoTIFF

* s. RD-01

Amplitude Mosaic (AMP)

The Amplitude Mosaic (mean value), the radar image, consists of the mosaic of the mean calibrated amplitude values of all contributing DTM scenes (at least 2 scenes, up to 10 scenes).

Filling Mask (FLM)

This Filling Mask is created during the WorldDEM™ generation process (Chapter 4.3).

Water Body Mask (WBM)

This Water Body Mask is created during the WorldDEM™ generation process (Chapter 4.3).

6 Customized WorldDEM™ Products

WorldDEM™ products are specified as the worldwide homogeneous and consistent products that are described in this document. On demand and subject to a feasibility study, it is possible to produce and deliver additional DEM variants based on customers' requests, e.g.:

- Projection and Format:
  - Vertical reference datum: WGS84 ellipsoid; EGM96
  - DEM in map projection, e.g. UTM
  - 16-bit signed GeoTIFF format
- Delivery of WorldDEM™ with specific editing rules:
  - Editing of additional features (to be discussed prior to ordering)

6.1 WorldDEM Derivatives

WorldDEM can be resampled to either 1 arcsecond (~30m) or 3 arcseconds (~90m). The standard resampling method is bilinear interpolation. Other options of resampling (pixel spacing, resampling method) are to be discussed prior to ordering.

<u>Please note:</u>

Water bodies and airport areas may not meet the criteria of the WorldDEM™ specifications after resampling, i.e.:

- the MMUs are not valid anymore,
- no 4-way connectivity constraint,
- individual lake/river pixels might be higher than those of neighboring lake/river features, etc.

7 Annex

7.1 Naming Convention

The file naming convention is standardised as follows:

WorldDEM_AAA_BB_YDD_EE_XGGG_HH
Example: WorldDEM_COR_04_S33_00_E138_00

The bold letters are fixed and remain unchanged at all times. The other letters have the following meanings (see Table 7-1). The file name always corresponds to the lower left corner coordinate (centre of Southwest pixel) of the AoI or bounding box corner, respectively.

Table 7-1: Naming Convention

Letter	Meaning
AAA	DEM Product Level: • COR = Core (unedited DEM) • DSM = WorldDEM (hydro-enforced, edited DEM) • DTM = DTM • VAR = customized / Variable
BB	Pixel Spacing: • 04: original spacing • 10: reduced to 1-arcsecond grid (on request) • 30: reduced to 3-arcsecond grid (on request)
YDD_EE_XGGG_HH	Geo-location of lower left corner in decimal degree e.g. N20_00_W120_00
Y	N (North) or S (South) hemisphere
DD	Latitude in Degree (Range: 0 - 90)
EE	Decimal Latitude Degree (Range: 0 - 99)
X	W (West) or E (East)
GGG	Longitude in Degree (Range: 0 - 180)
HH	Decimal Longitude Degree (Range: 0 - 99)

7.2 Additional data sets

The following data is equally provided with each of the WorldDEM™ products.

7.2.1 Metadata

The Metadata contains information on the input products, editing process, statistical parameters and general information for all delivered product components. The Metadata is ISO 19115 compliant.

The Metadata is delivered as an xml-file. The ProductInfo.html file shows main metadata information in a style sheet format (based on .xsl file).

7.2.2 Source Mask

The Source Mask (SRC) is a vector file (kml) containing the information of the data scenes used for DEM processing. This file includes information about the acquisition ID, data scene number, data acquisition date and time as well as information about the height of ambiguity of the included data scenes.

7.2.3 Quicklooks

Quicklook images are provided with the $WorldDEM_{core}$, the WorldDEM™ and the WorldDEM DTM product package. All raster data (DEM, Amplitude Mosaics and Masks) are available as 8–bit data in GeoTIFF format. The original spatial resolution is reduced by a factor of 10.

Two DEM quicklooks are provided, which are refined to colourised shaded reliefs:

- Representing absolute DEM values: colour table with respect to a global elevation range (between -450m and 9000m)
- Representing relative DEM values: colour table adapted to AoI statistics (min/max)

Additionally, kml files linked to these quicklooks are delivered with the data for easy visualisation in GoogleEarth and GIS platforms.

7.3 Product File Structure

All product files are structured under the delivery folder (see Figure 7-1, Figure 7-2, and Figure 7-3) as follows:

- **Xml** file (Metadata)
- **INFO** folder containing the following information:
    - For displaying metadata on stylesheet: product info (html), stylesheet data (xsl), quicklook files (jpg), logo (png), additional stylesheet data (css), legend file (png)
    - Applicable Contract / Licence Terms document (pdf)
- **DEM** folder containing elevation data (GeoTIFF)
- **AUXFILES** folder containing all auxiliary data layers ($WorldDEM_{core}$) or quality layers ($WorldDEM^{TM}$, WorldDEM DTM) (all GeoTIFF)
- **PREVIEW** folder containing all quicklooks (GeoTIFF) as well as all kml-files for visualisation in GoogleEarth including the Source Mask (SRC).

For file naming convention see Chapter 7.1.

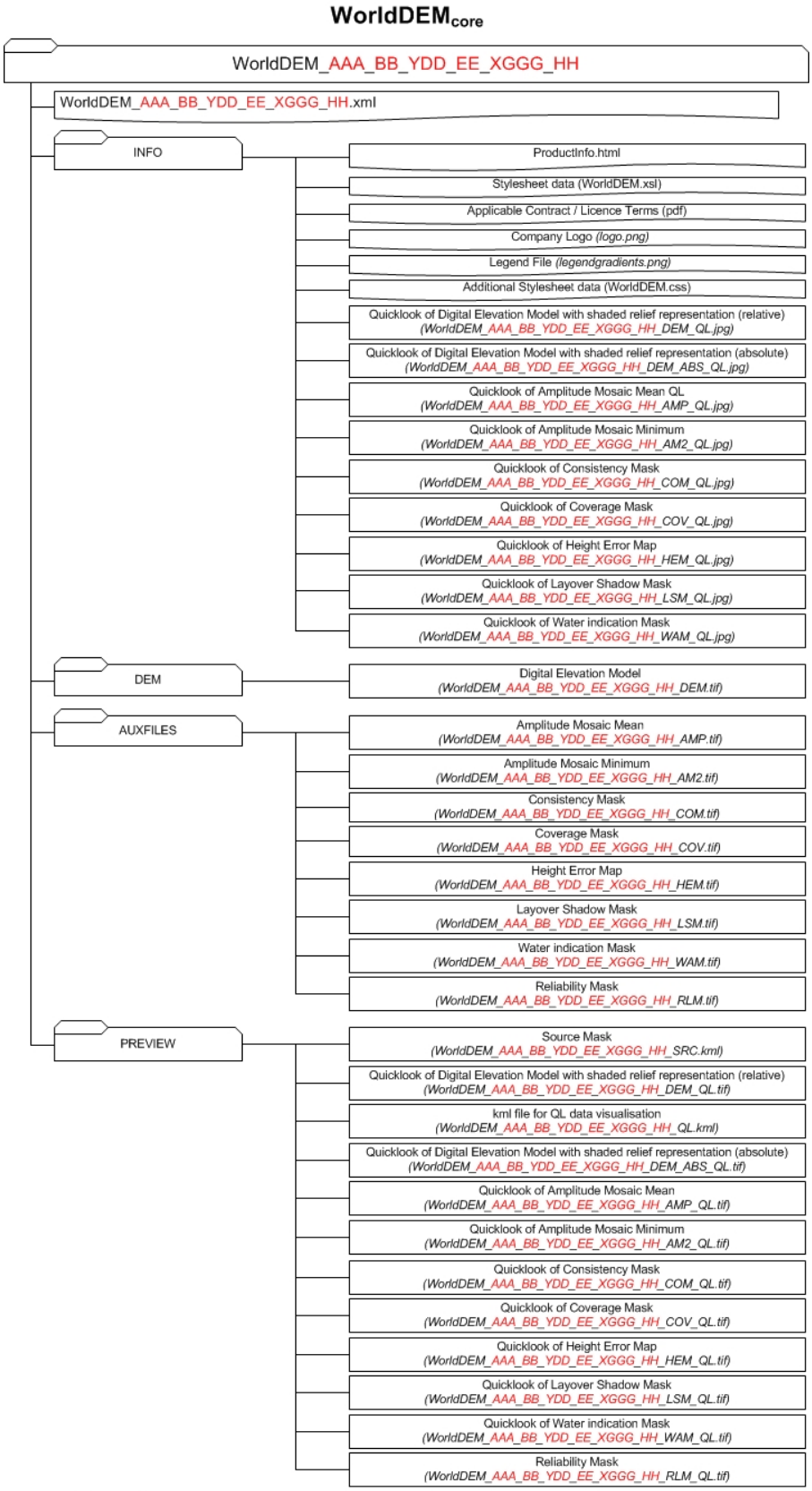

Figure 7-1: WorldDEM$_{core}$ Product Structure

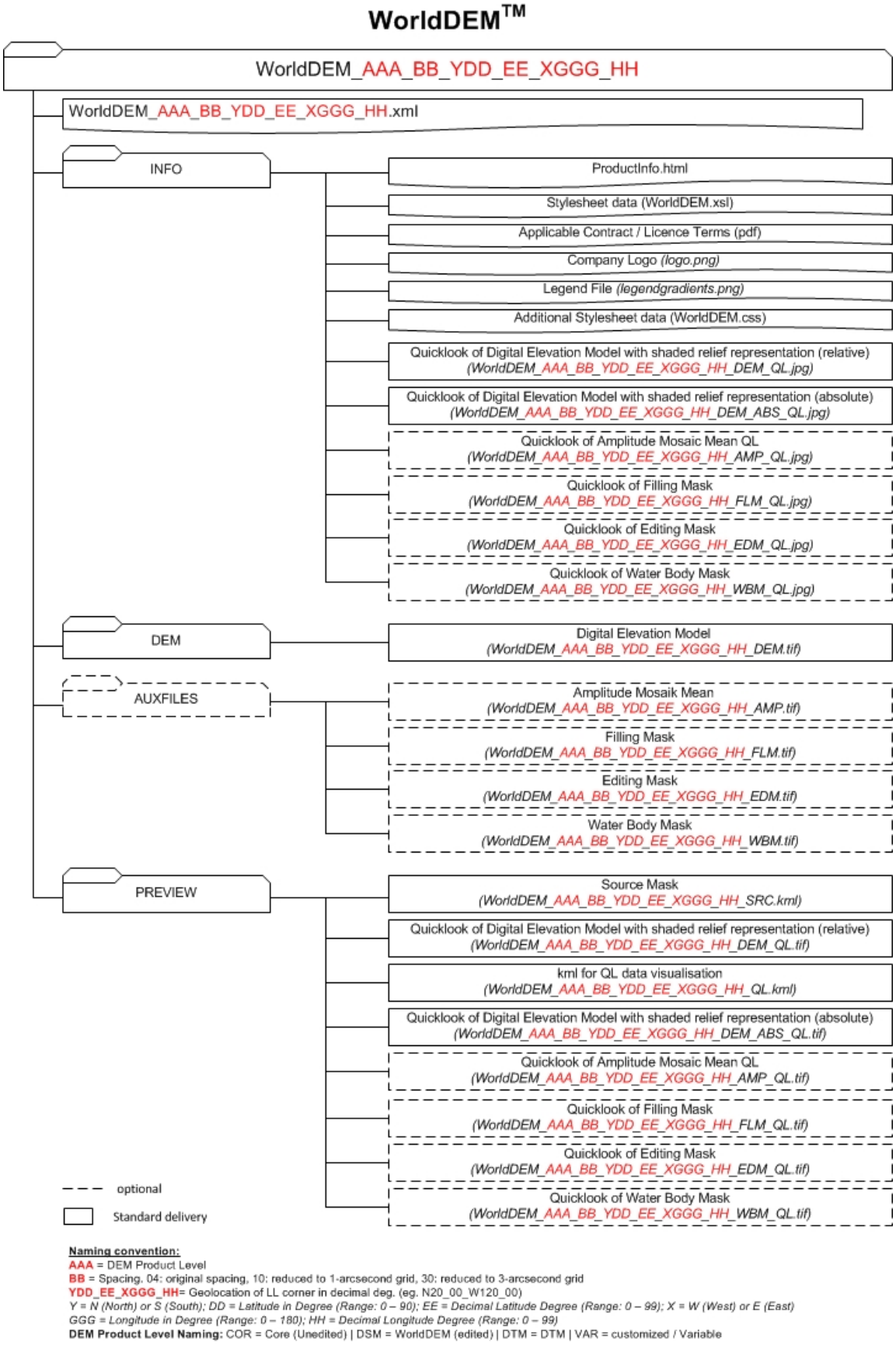

Figure 7-2: WorldDEM™ Product Structure

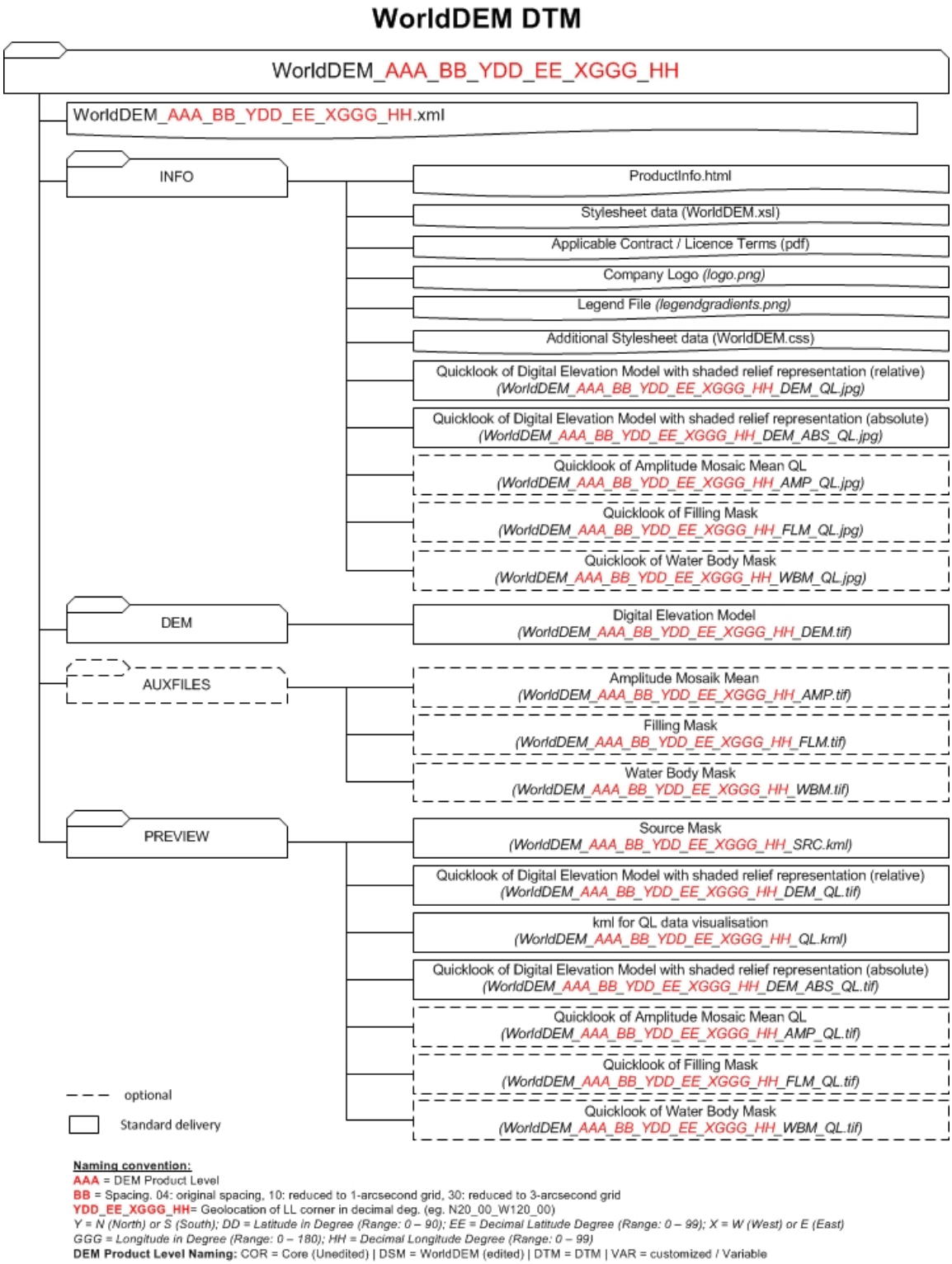

Figure 7-3: WorldDEM DTM Product Structure