TanDEM-X

The Earth in Three Dimensions

TanDEM-X

Global 3D-Mapping at Unprecedented Accuracy

On June 21, 2010 the TanDEM-X Mission was launched and opened a new era in space-borne radar remote sensing. The first formation flying radar system was built by extending the TerraSAR-X Synthetic Aperture Radar (SAR) mission by a second, TerraSAR-X-like satellite TanDEM-X. The resulting large single-pass SAR interferometer features flexible baseline selection, enabling the acquisition of highly accurate cross-track interferograms not impacted by temporal decorrelation and atmospheric disturbances. The primary objective of the mission – the generation of a global Digital Elevation Model (DEM) with unprecedented accuracy – was achieved in 2016.

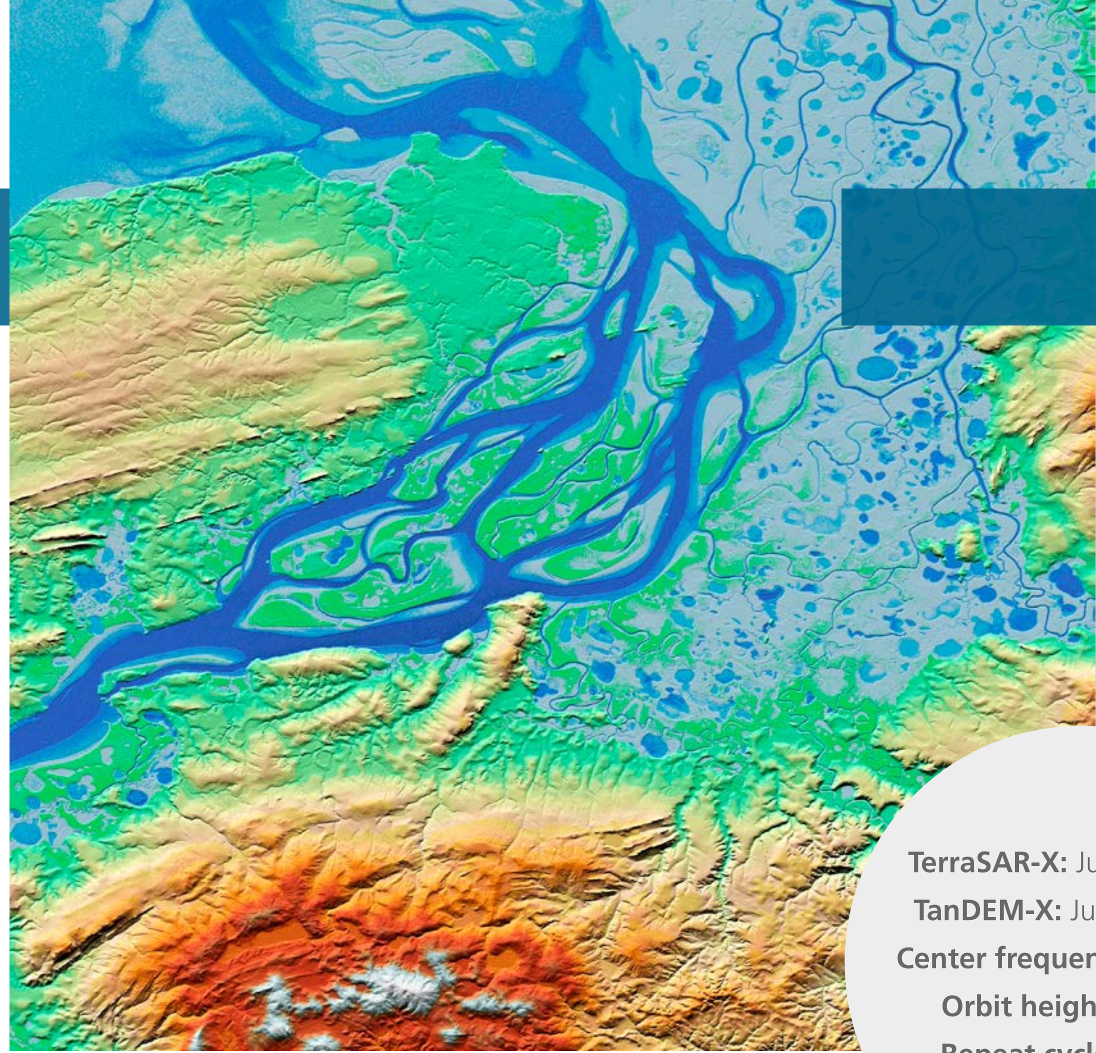
Beyond this primary mission objective TanDEM-X is also an important pre-cursor for future SAR satellite formations allowing to demonstrate novel SAR techniques, with focus on multi-static SAR, polarimetric SAR interferometry and digital beamforming. A dedicated science phase after the global DEM acquisitions included up to 4 km cross-track baselines, operation in the so-called Dual-Receive Antenna mode, as well as a period in pursuit monostatic flight formation.

While working on the global DEM, it became clear that Earth's surface is highly dynamic – changes in the height of glaciers, permafrost areas and forests were to be expected, but changes due to agricultural activities and infrastructure projects also leave clear traces and can be measured. Observing these processes and determining them quantitatively is not only of great scientific interest, but also has socio-political relevance with regard to climate change. For this reason, in 2017 the decision was made to continue the mission with a focus on topographical changes. By repeatedly observing certain areas, a time series of data is created. The dataset gradually grows and, in addition to the three spatial dimensions, contains a fourth dimension – time – revealing new, previously hidden insights. For example, the growth and degradation of forests can be measured. Repeated height measurements also allow the observation and quantification of the melting of glaciers and ice sheets caused by global warming.

Despite being well beyond their design lifetime, both satellites are still fully functional and have enough consumables for several additional years. Therefore, bistatic operations continue with a focus on changes in the cryosphere, biosphere and densely populated urban areas.

Specification of the Global TanDEM-X DEM

Parameter	Definition	Requirement
Relative Vertical Accuracy	90% linear point-to-point error in 1°×1° cell	2 m (slope < 20%) 4 m (slope > 20%)
Absolute Vertical Accuracy	90% linear error	10 m
Spatial Resolution	independent pixels	12 m (0.4 arc sec)



TanDEM-X DEM of the frozen Pjasina river meandering into the Kara Sea in northern Russia

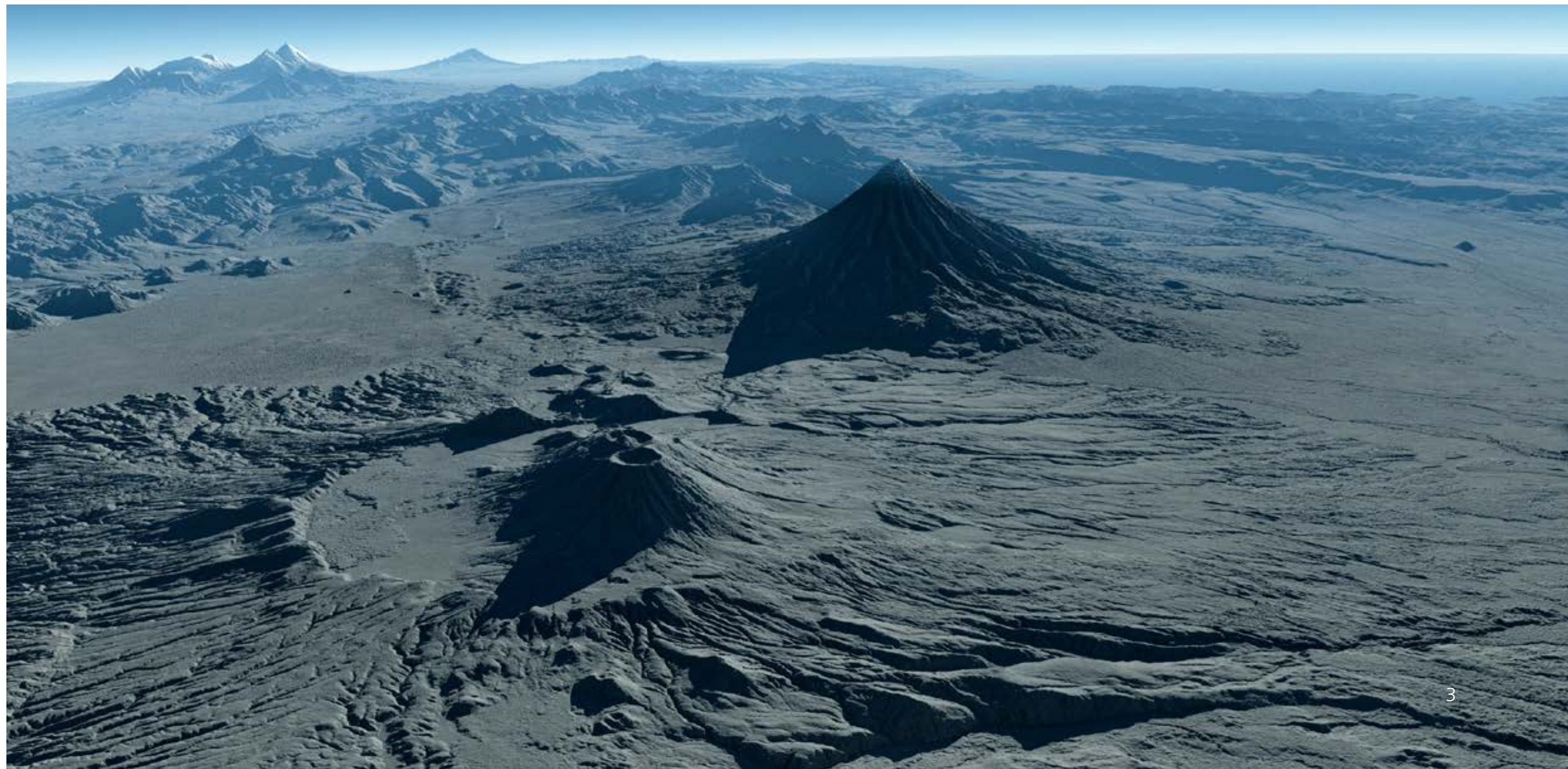
The TanDEM-X Mission Concept

The TanDEM-X mission is an extension of the TerraSAR-X radar mission, co-flying a second almost identical satellite in a close formation. The TerraSAR-X satellite (TSX), as basis for TanDEM-X, was successfully launched into a 514 km, 11 day repeat cycle, sun-synchronous dusk-dawn orbit on June 15, 2007. Late in the development, necessary features required for the mission TanDEM-X were implemented on TSX. Examples are additional X-band horn antennas for inter-satellite phase synchronization, a dual-frequency GPS receiver for precise orbit and baseline determination, improved radio frequency phase stability of the SAR instrument, and pulse repetition frequency synchronization based on GPS as a common time reference. The second satellite (called TDX, launched on June 21, 2010) is mostly a rebuild of TSX with only minor modifications like an additional cold gas propulsion system for formation keeping maneuvers, double-sized on-board solid-state memory for increased data recording capacity, and an additional S-band receiver to enable the receptiona of telemetry and GPS position information broadcast by TSX. The instruments on both satellites are advanced high-resolution X-band (center frequency 9.65 GHz, chirp bandwidth up to 300 MHz) synthetic aperture radars, which can be operated in staring and sliding Spotlight, Stripmap, and ScanSAR modes.

TerraSAR-X: June 15, 2007
TanDEM-X: June 21, 2010
Center frequency: 9.65 GHz
Orbit height: 514 km
Repeat cycle: 11 days

Flying at a typical distance of a few hundred meters the two satellites perform single-pass interferometry and acquire cross-track interferograms. By evaluating the phase difference between two coherent radar signals acquired from slightly different spatial positions, TanDEM-X is able to measure the range difference between the two satellites and a given scatterer on the ground with millimetric precision. The height of the scatterer is inferred from this range difference by geometric triangulation.

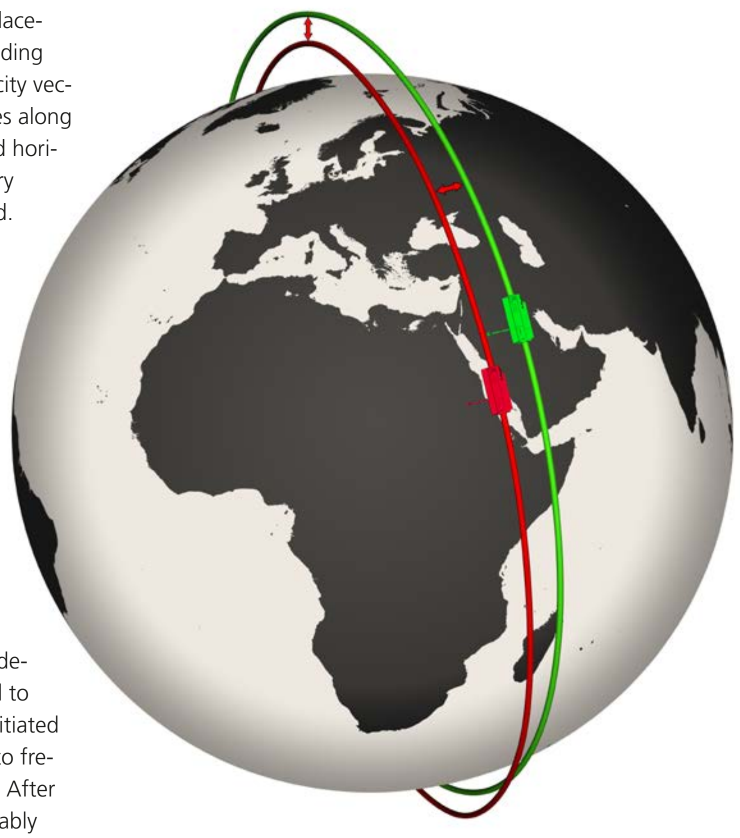
Perspective view of the Krascheninnikov Caldera (in the front) and the 3528 m high Kronotsky volcano, rising up as an almost perfect cone. At the horizon on the left one can recognize the Kljutschevskoi volcano, with 4835 m the highest peak on the Russian Kamchatka peninsula.



Orbit Configuration and Formation Flying

The TanDEM-X operational scenario requires the coordinated operation of two satellites flying in close formation. The so-called Helix formation combines an out-of-plane (horizontal) orbital displacement by small differences in the right ascension of the ascending nodes with a radial (vertical) separation by different eccentricity vectors resulting in a helix-like relative movement of the satellites along the orbit. Since the two orbits never cross (i.e., the combined horizontal/radial separation is always larger than 120 m), arbitrary shifts and drifts of the satellites along their orbits are allowed. This enables safe spacecraft operation without the necessity for autonomous control. For a complete mapping of the Earth with dedicated heights of ambiguity the Helix formation parameters, namely the horizontal and vertical distances between the satellites and the so-called phase of libration, are regularly adjusted. Southern and northern latitudes can be mapped with the same formation by using ascending orbits for one hemisphere and descending orbits for the other.

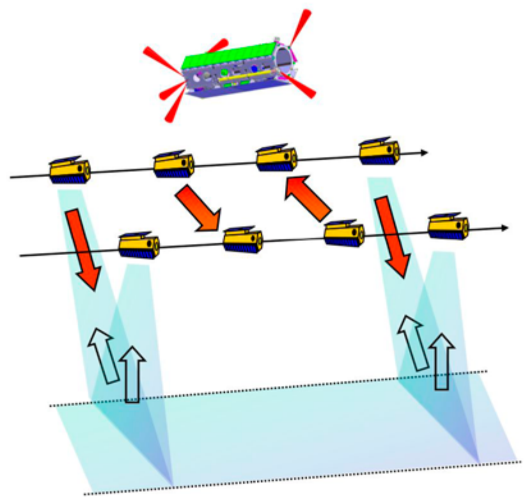
The satellite orbits are controlled according to the relative eccentricity/inclination vector control concept, where daily maneuver pairs compensate for the differential forces acting on the formation (mainly due to Earth oblateness and small deviations of previous orbit control maneuvers when compared to the nominal orbit position). Since the close formation was initiated in October 2010, the formation geometry has been subject to frequent changes as implied by the TanDEM-X acquisition plan. After thirteen years of formation flying, the two satellites have reliably and precisely executed almost 12,000 orbit control maneuvers, mainly for formation reconfiguration and maintenance, but also for TSX orbit control and debris collision avoidance. At an orbital velocity of 27,400 km/h, the achieved control accuracy in cross-track (two dimensional) is below 5 m (RMS) for stable geometries and below 10 m for horizontally drifting formations, and 30 m (one dimensional, RMS) in along-track direction.



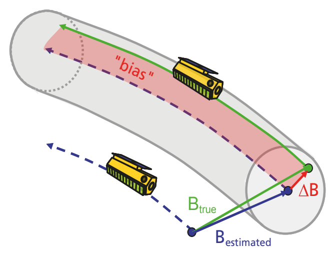
Helix satellite formation. Red: TSX, Green: TDX; Typical baseline values vary from 120 m to 500 m.

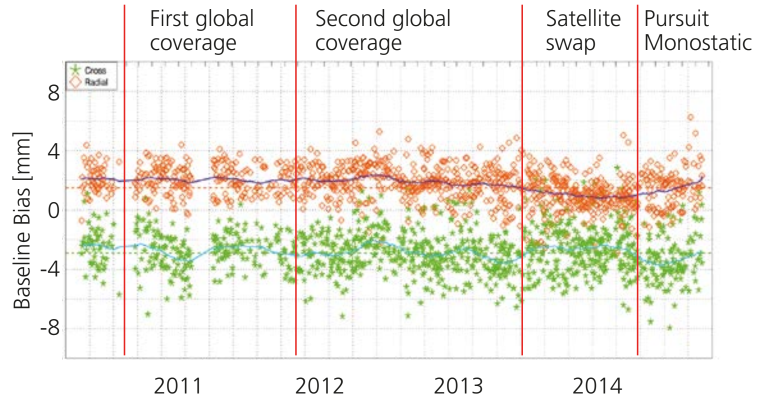
Phase Synchronization

A peculiarity of the bistatic data acquisition is the use of independent oscillators for the modulation and demodulation of the radar pulses. Any deviation between the two oscillators causes residual modulations of the recorded azimuth signal. The stringent requirements for interferometric phase stability in the bistatic mode hence require an appropriate relative phase referencing between the two SAR instruments. For TanDEM-X, a dedicated inter-satellite X-band synchronization link has been established: the nominal bistatic SAR data acquisition is briefly interrupted, and radar pulses are exchanged between the two satellites using dedicated synchronization horn antennas. On ground, a correction signal can be derived from the recorded synchronization pulses. This compensates the oscillator-induced phase errors in the bistatic SAR signal to better than 1°, corresponding to residual height error contributions in the decimeter range.



TanDEM-X Phase Synchronization: Exchange of synchronization pulses via an intersatellite link using dedicated synchronization horn antennas





Schematic drawing and the corresponding measurement of the baseline bias, which has been estimated at millimetric accuracy from repeated acquisitions of globally distributed flat test sites with known height.

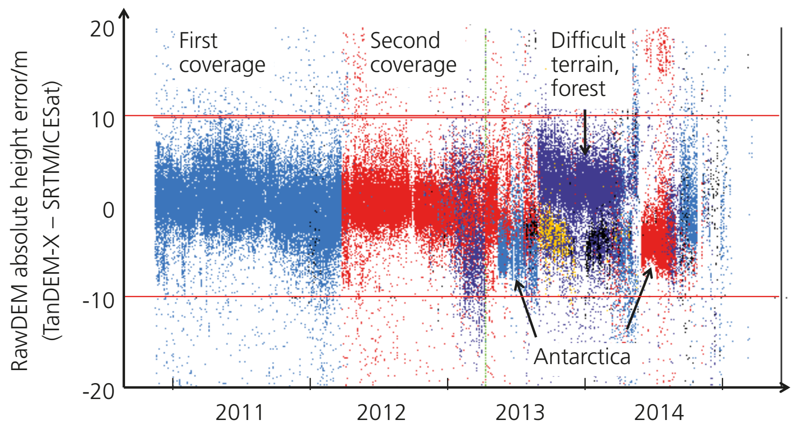
Calibration of the Bistatic Interferometer

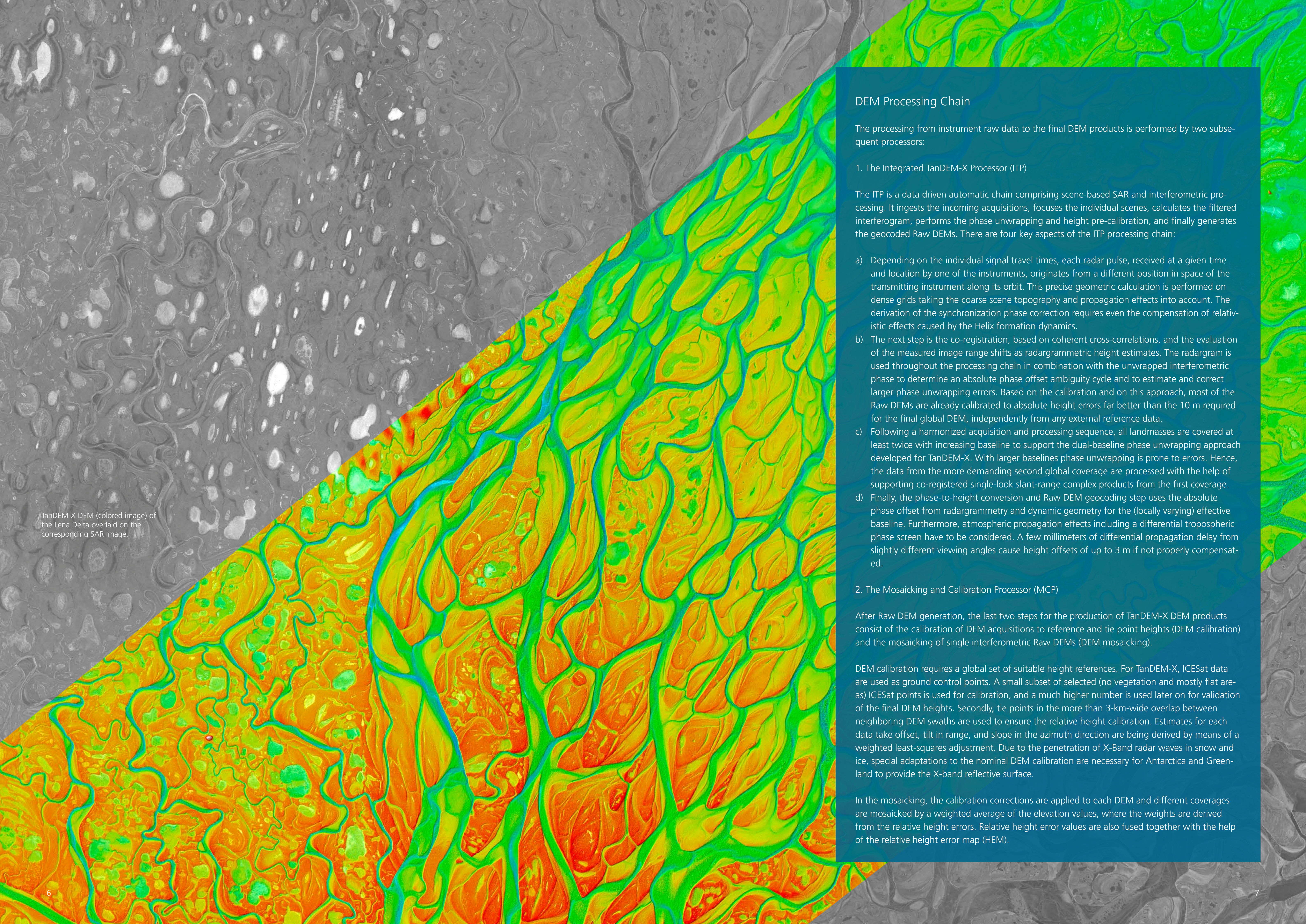
Data takes for the global DEM are collected in bistatic Stripmap mode with a swath width of 30 km. In a fully automated first processing step, the data takes are divided into individual scenes, so-called Raw DEMs, with an extent of 30 km in range × 50 km in azimuth. Each Raw DEM already needs to be as close as possible to its real height to allow for an accurate geocoding and to facilitate the second processing step in which blocks of the different scenes are calibrated against their neighbors and against ICESat reference heights.

The interferometric calibration includes three different parts:

- Precise baseline determination is performed by a double differential evaluation of GPS carrier phase measurements. However, primarily due to uncompensated offsets from the SAR antenna phase centers, the relative satellite positions derived from GPS measurements are biased. This baseline bias has been estimated at millimetric accuracy from repeated acquisitions of globally distributed flat test sites with known height.
- The interferometric phase is ambiguous by the wavelength, and thus the correct ambiguity band needs to be resolved. This can be achieved by radargrammetric height determination, which exploits the unambiguous radar signal travel times. For this, a highly precise delay calibration is required to compensate different time delays in the instruments that can vary depending on radar parameters
- The final adjustment is performed by calibrating the phase offset between both acquisitions based on a comparison with SRTM and ICESat as reference. It has been adjusted such that more than 90% of all Raw DEMs initially are within ±10 m versus SRTM/ICESat.

Precise bistatic system calibration performed by comparing the absolute height of the scenes with SRTM/ICESat as an independent reference. The absolute height of the majority of the scenes is well within +/-10 m even before final DEM calibration and mosaicking.





TanDEM-X DEM (colored image) of the Lena Delta overlaid on the corresponding SAR image.

DEM Processing Chain

The processing from instrument raw data to the final DEM products is performed by two subsequent processors:

1. The Integrated TanDEM-X Processor (ITP)

The ITP is a data driven automatic chain comprising scene-based SAR and interferometric processing. It ingests the incoming acquisitions, focuses the individual scenes, calculates the filtered interferogram, performs the phase unwrapping and height pre-calibration, and finally generates the geocoded Raw DEMs. There are four key aspects of the ITP processing chain:

a) Depending on the individual signal travel times, each radar pulse, received at a given time and location by one of the instruments, originates from a different position in space of the transmitting instrument along its orbit. This precise geometric calculation is performed on dense grids taking the coarse scene topography and propagation effects into account. The derivation of the synchronization phase correction requires even the compensation of relativistic effects caused by the Helix formation dynamics.
b) The next step is the co-registration, based on coherent cross-correlations, and the evaluation of the measured image range shifts as radargrammetric height estimates. The radargram is used throughout the processing chain in combination with the unwrapped interferometric phase to determine an absolute phase offset ambiguity cycle and to estimate and correct larger phase unwrapping errors. Based on the calibration and on this approach, most of the Raw DEMs are already calibrated to absolute height errors far better than the 10 m required for the final global DEM, independently from any external reference data.
c) Following a harmonized acquisition and processing sequence, all landmasses are covered at least twice with increasing baseline to support the dual-baseline phase unwrapping approach developed for TanDEM-X. With larger baselines phase unwrapping is prone to errors. Hence, the data from the more demanding second global coverage are processed with the help of supporting co-registered single-look slant-range complex products from the first coverage.
d) Finally, the phase-to-height conversion and Raw DEM geocoding step uses the absolute phase offset from radargrammetry and dynamic geometry for the (locally varying) effective baseline. Furthermore, atmospheric propagation effects including a differential tropospheric phase screen have to be considered. A few millimeters of differential propagation delay from slightly different viewing angles cause height offsets of up to 3 m if not properly compensated.

2. The Mosaicking and Calibration Processor (MCP)

After Raw DEM generation, the last two steps for the production of TanDEM-X DEM products consist of the calibration of DEM acquisitions to reference and tie point heights (DEM calibration) and the mosaicking of single interferometric Raw DEMs (DEM mosaicking).

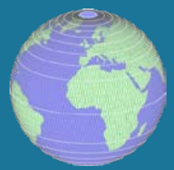
DEM calibration requires a global set of suitable height references. For TanDEM-X, ICESat data are used as ground control points. A small subset of selected (no vegetation and mostly flat areas) ICESat points is used for calibration, and a much higher number is used later on for validation of the final DEM heights. Secondly, tie points in the more than 3-km-wide overlap between neighboring DEM swaths are used to ensure the relative height calibration. Estimates for each data take offset, tilt in range, and slope in the azimuth direction are being derived by means of a weighted least-squares adjustment. Due to the penetration of X-Band radar waves in snow and ice, special adaptations to the nominal DEM calibration are necessary for Antarctica and Greenland to provide the X-band reflective surface.

In the mosaicking, the calibration corrections are applied to each DEM and different coverages are mosaicked by a weighted average of the elevation values, where the weights are derived from the relative height errors. Relative height error values are also fused together with the help of the relative height error map (HEM).

2010

Commissioning Phase
- Calibration and operationalization

2011



1st Global Coverage
- Small baseline (~200 m)
- Height of Ambiguity ~ 50 m

2012

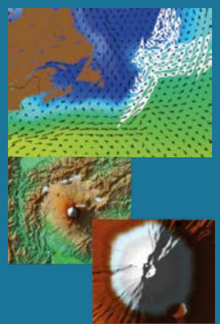
2nd Global Coverage
- Increased baseline (~300 m),
- Height of Ambiguity ~ 35 m

Combination:
- Dual-baseline phase unwrapping
- Improved height accuracy

2013

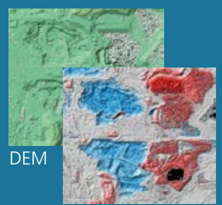
3rd Year Acquisitions
- Antarctica
- Different viewing geometry to account for shadow & layover
- Deserts

2014-2016



Science Phase
- Exploitation of the scientific potentials of the mission
- Acquisitions with special formations
- Generation of High Resolution DEMs

2017-2020



TanDEM-X DEM 2020
- Acquisitions for a second global DEM
- Additional Change Layer with differences between 2010-2013 and 2016-2022

2020-2022

Science Phase 2020-2022
- Scientific acquisitions
- Main areas of interest: forest, glaciers/permafrost, urban areas

2022-2028ff

TanDEM-X 4D Phase
- Continuous monitoring of topographic changes on Earth
- Prioritized areas: forest, glaciers, areas with large elevation changes
- Generation of DEM Change Maps

Acquisition Planning

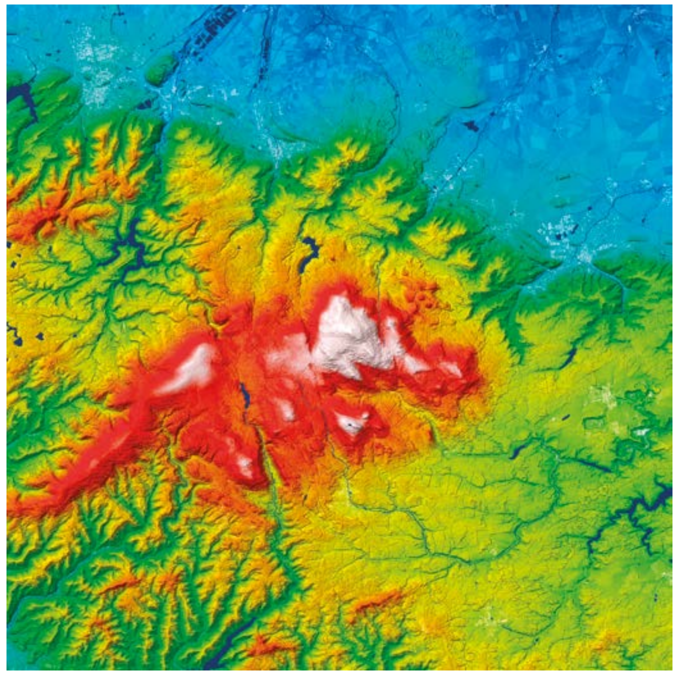
The acquisition strategy to generate the global DEM has been driven by the product specification for the relative height accuracy, which is in turn directly related to the phase noise that can be quantified through the interferometric coherence, and the perpendicular baseline or, equivalently, the height of ambiguity. The latter needs, on the one hand, to be sufficiently small to ensure a good relative height accuracy on global scale, and, on the other hand, it must be large enough to guarantee a robust phase unwrapping process. The interferometric coherence has been monitored throughout the entire mission and has served as key parameter for optimizing the global acquisition strategy.

Nominal DEM acquisitions were performed in right-looking observation mode in ascending/descending orbits over the Northern and Southern hemisphere, respectively. In 2011 a global acquisition of Earth's landmasses excluding Antarctica was carried out. According to the acquisition strategy, the orbit formation was properly adjusted in order to keep a height of ambiguity of about 50 m for all different incidence angles and latitudes. For the acquisitions of the second global coverage in 2012 the target height of ambiguity was reduced from 50 m to 35 m, where a decrease by a factor of 0.7 was empirically found to be optimal to assimilate the two acquisitions by the dual-baseline phase unwrapping approach. The two global coverages were performed using swath positions shifted against each other by half of the swath width to reduce the impact of SNR degradation at the swath edges, resulting in homogeneous height performance over the whole access range.

Continuous performance analysis and monitoring during the first two years suggested the need to perform further acquisitions over densely forested areas, e.g., over the Amazon rainforest in Brazil or the tropical forest in South East Asia. Moreover, complementary data takes from ascending and descending orbits have been acquired over mountainous regions and at steeper incidence angles over sandy deserts. To complete the global DEM generation, Antarctica has also been acquired twice during the austral winter to ensure stable dry-snow conditions. Due to the retrograde polar orbits the central part of Antarctica was covered by left-looking observations using shallower incidence angles above 50°.

TanDEM-X features unique capabilities, including along-track interferometry, and new bistatic and multistatic SAR techniques, that support numerous secondary mission objectives. Some of these experiments were directly performed during the global DEM acquisition phase, when suitable satellite formation geometries were available. In a dedicated science phase after the global DEM acquisitions extreme formation geometries with up to up to 4 km cross-track baselines and in pursuit monostatic flight formation at an along-track distance of about 70 km have been demonstrated. This mission phase also included operation in the so-called Dual-Receive Antenna mode to support data takes in quad-polarization as well as acquisitions for high-resolution DEMs.

While working on the global DEM, it became clear that the performance of TanDEM-X allows to capture even small topographic changes occurring on short time scales of one year or less. Observing these changes and determining them quantitatively is not only of great interest for science, but also has socio-political relevance with regard to climate change. For this reason, the decision was made to continue the mission with a focus on topographical changes. In addition to the three spatial dimensions, now also time as the fourth dimension comes into play and opens detailed insights in the dynamic on the Earth's lands surface.

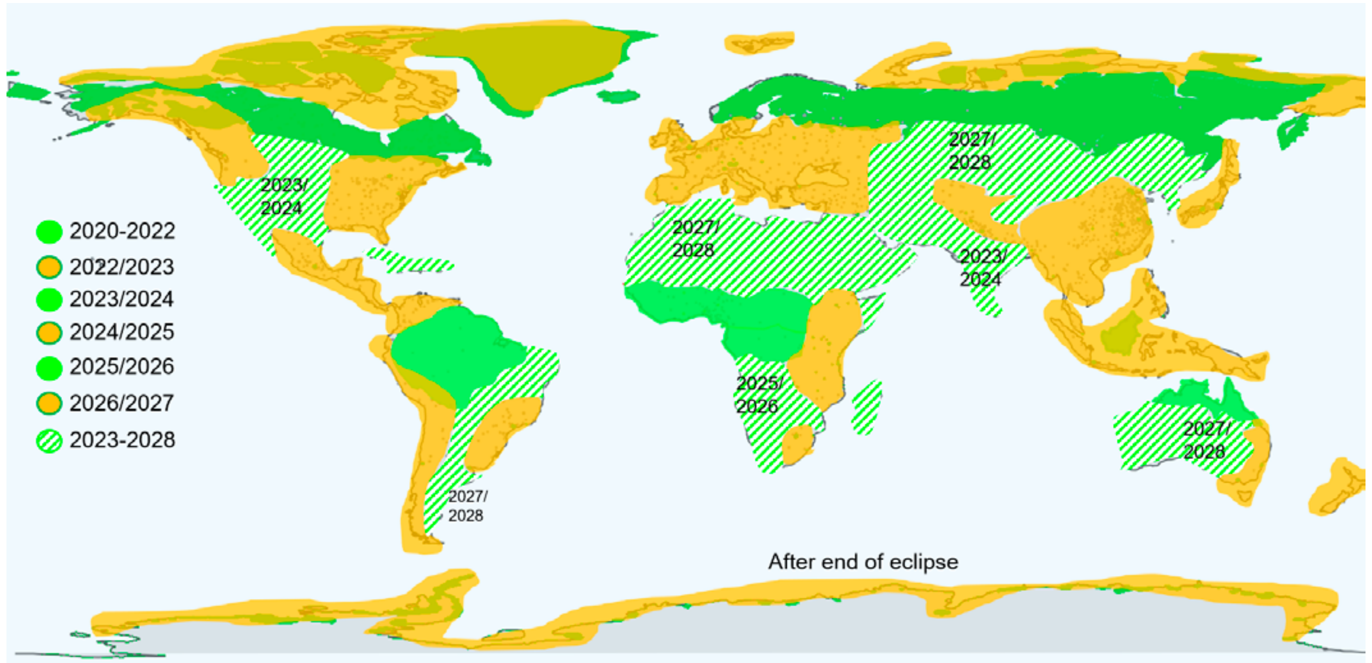


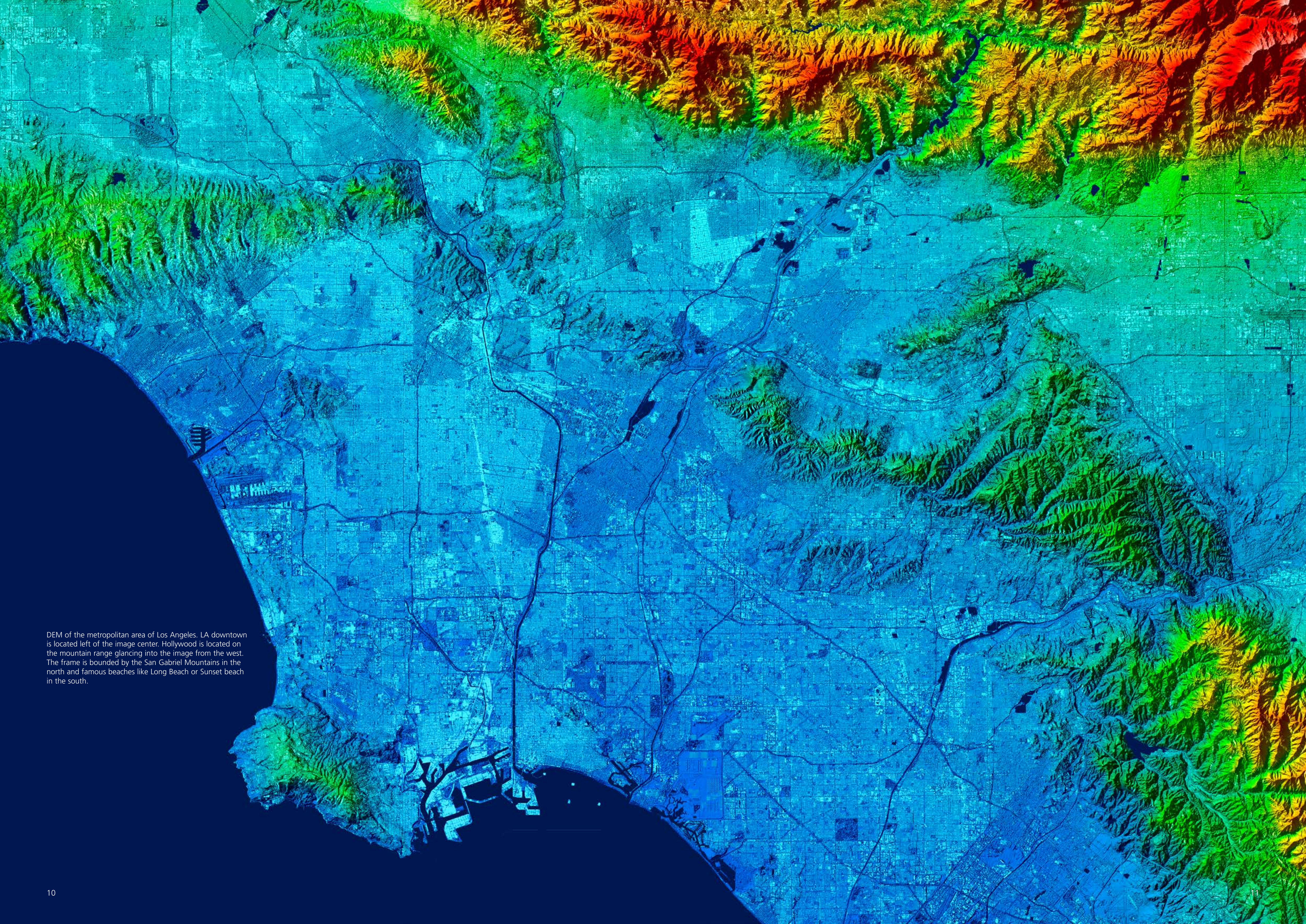
DEM visualization of Mount Brocken, Germany

The first years of the bonus phase concentrated on a re-acquisition of the global land surfaces. By 2020, the satellites twins had mapped Earth's entire landmasses once more as the basis for a new independent up-to-date global DEM, the TanDEM-X DEM 2020. In a second science phase, tropical rainforests were mapped both with nominal baselines in order to derive DEMs as well as with large baselines to allow forest/non-forest classification. In addition, boreal forests, the large arctic glaciers and the permafrost belt in northern latitudes were covered at least once. Finally, the 2000 largest cities on Earth were acquired with various baselines and from different viewing geometries in order to allow 3D reconstruction of urban areas.

To emphasize the monitoring of topographic changes and the importance the time of the 3D acquisitions, the mission entered in 2022 the so-called TanDEM-X 4D phase – time being the fourth dimension – with regularly repeated observations of dynamic regions. Non-forested areas where the comparison between first and second global DEM revealed considerable height differences, are covered again. These areas involve large mountain ranges like the Himalayas, the Andes, or the Rocky Mountains. In addition, also Europe and China are mapped. It takes about one year to cover these areas. In the subsequent year, DEMs over forests and permafrost regions, that have been acquired during the second science phase will be re-acquired. This biennial sequence will then be repeated until the end of the mission. Areas with lower height variation will be interspersed during the forest/permafrost acquisitions from year to year to collect data for a further update of the global DEM by 2028. Finally, also the outer regions of Antarctica will be covered again. Contrary to the global DEM phase, this will be executed after the eclipse phase, i.e., around the end of the austral winter. This became necessary to preserve the aging batteries. Battery preservation also requires to reduce the acquisition capacity by shortening the length of individual data takes and by increasing the pause in between.

Areas to be acquired during the TanDEM-X 4D phase with forests in solid green, regions with larger changes in orange and lower prioritized areas in dashed green.





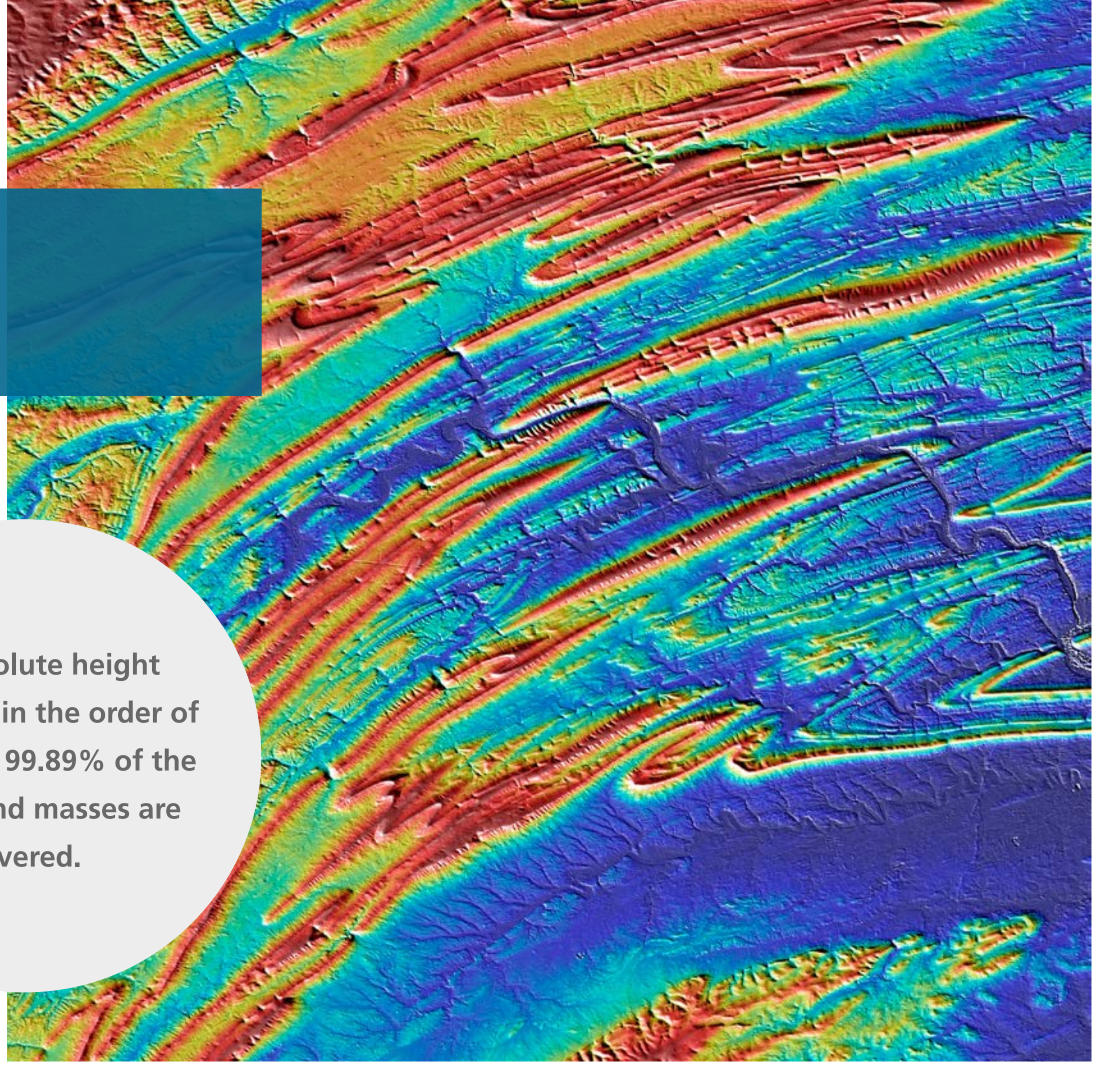
DEM of the metropolitan area of Los Angeles. LA downtown is located left of the image center. Hollywood is located on the mountain range glancing into the image from the west. The frame is bounded by the San Gabriel Mountains in the north and famous beaches like Long Beach or Sunset beach in the south.

DEM Performance of the Global TanDEM-X DEM (2016)

The global TanDEM-X DEM is partitioned into more than 19,000 so-called geocells covering 1° × 1° in latitude and longitude at the equator. The performance presented in this section is assessed separately for three different classes of DEM geocells according to the dominant land cover type: forest geocells, characterized by more than 60% of forest coverage; ice geocells, with more than 60% of ice or snow coverage; and generic geocells, i.e., all other geocells. The first two classes are strongly affected by volume decorrelation.

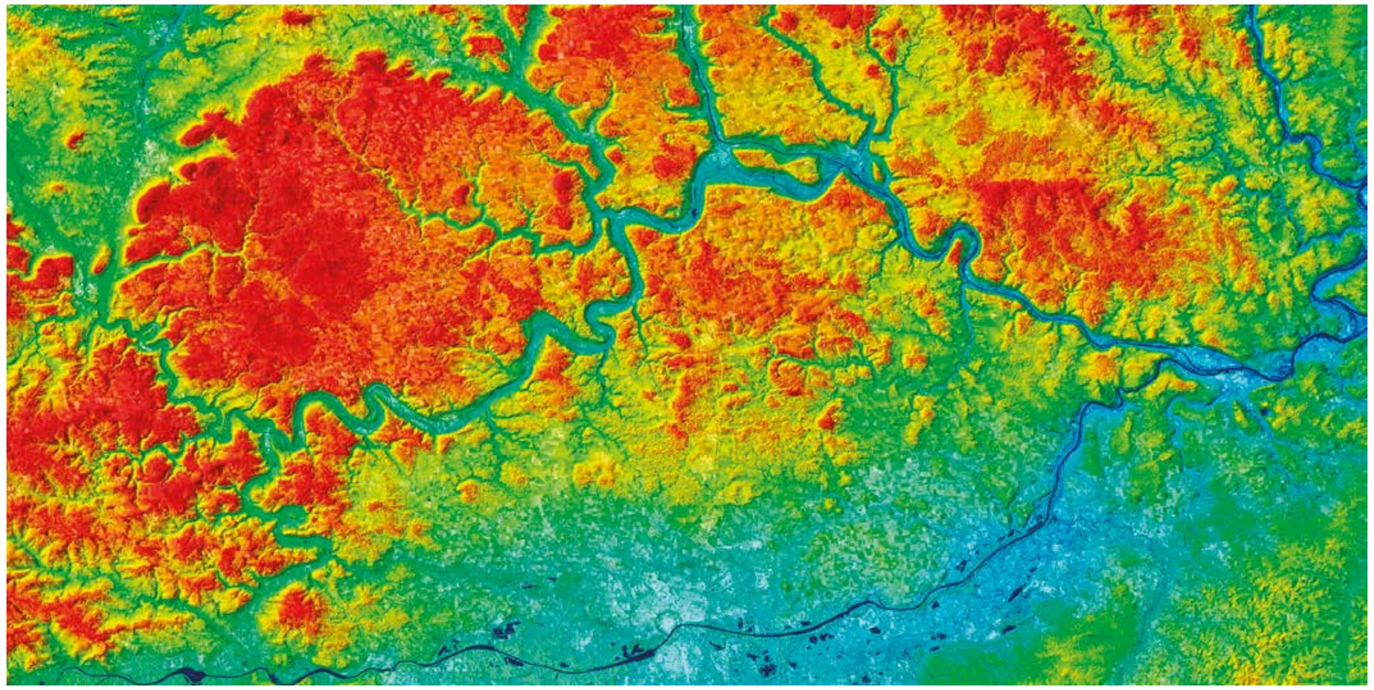
The absolute vertical accuracy represents the uncertainty in the height of a point with respect to the WGS84 ellipsoid caused by uncorrected, slow-changing systematic errors. The evaluation of the final TanDEM-X DEM performance is based on the difference between TanDEM-X and ICESat points not used in the DEM calibration. On a global scale, the performance in terms of absolute vertical accuracy has been evaluated using the best 1000 ICESat validation points per DEM geocell, characterized by the lowest spatial variance, and thus tending towards moderate-relief terrain. The prioritization of flat regions in the evaluation does not compromise the validity of the proposed method, as the main error sources are the remaining tilts and low-varying trends, which affect the entire geocell. The results confirm the outstanding capabilities of the system, with an overall absolute height accuracy at a 90% confidence level of just 3.49 m, which is well below the 10 m mission specification. Excluding highly vegetated and snow/ice-covered regions characterized by radar wave penetration phenomena and consequently strongly affected by volume decorrelation, the absolute height accuracy improves to 0.88 m (for generic geocells only).

The absolute height accuracy is in the order of one meter. 99.89% of the Earth's land masses are covered.



TanDEM-X DEM of the northern part of the Appalachian Mountains and Juniata River cutting through it (USA)

The valley of the Altmühl is deeply carved into the Franconian Jura-mountains. The valley was originally formed by the "Ur-Donau" several 100.000 years ago.



The relative height accuracy – or point-to-point vertical accuracy – describes the precision of the local height differences and only accounts for random errors. The relative height accuracy for each input observation can be directly estimated from the interferometric coherence and the number of looks by assuming a zero-mean Gaussian distribution. For each geocell of the mosaicked TanDEM-X DEM, the estimation of the linear point-to-point confidence level for the specified height accuracy is derived from the height error map (HEM) – separately for flat (predominant slope lower than 20%) and steep terrain (predominant slope higher than 20%).

Geocells dominated by forest or mostly covered by snow or ice are affected by volume decorrelation phenomena, which artificially degrade the interferometric coherence. For this reason, they are excluded from the validation process. With this exclusion, the mission specification at 90% confidence level (2 m and 4 m for flat and steep terrain, respectively) is met on a global scale for 97.76% of all geocells. The global DEM is not only highly accurate but is also stands out for its completeness. Gaps in the TanDEM-X global DEM dataset, so-called voids over land, account for only 0.107% of the entire Earth's landmass or, in other words, the data coverage is better than 99.89%. Besides the global validation, several additional quality analyses have been performed using local reference data sets, such as kinematic GPS tracks, lidar, and other global DEM data. The results are well in line with the numbers reported above and confirmed the high accuracy of the height data.

The generation of the global DEM, which is the primary mission objective, was successfully completed in September 2016. DEM performance specifications have all been met or exceeded. In the case of the absolute height accuracy, the final result is one order of magnitude better than the 10 m requirement. A world-wide, consistent and up-to-date DEM of that quality is of fundamental importance for a wide range of scientific and commercial applications. The edited version of the TanDEM-X DEMs are among the few remote sensing data sets that are commercially viable and have been supplied to the ESA/European Commission Copernicus Programme, i.e. the so-called Copernicus DEM is basically an edited version of the TanDEM-X Global DEM and is free and open at a posting of 30 m and 90 m. The scientific community is being served by DLR providing access even to the full resolution 12 m DEMs at no costs via a standard Announcement of Opportunity process. Currently, more than 4,000 scientists from 97 countries are registered on the TanDEM-X science server.

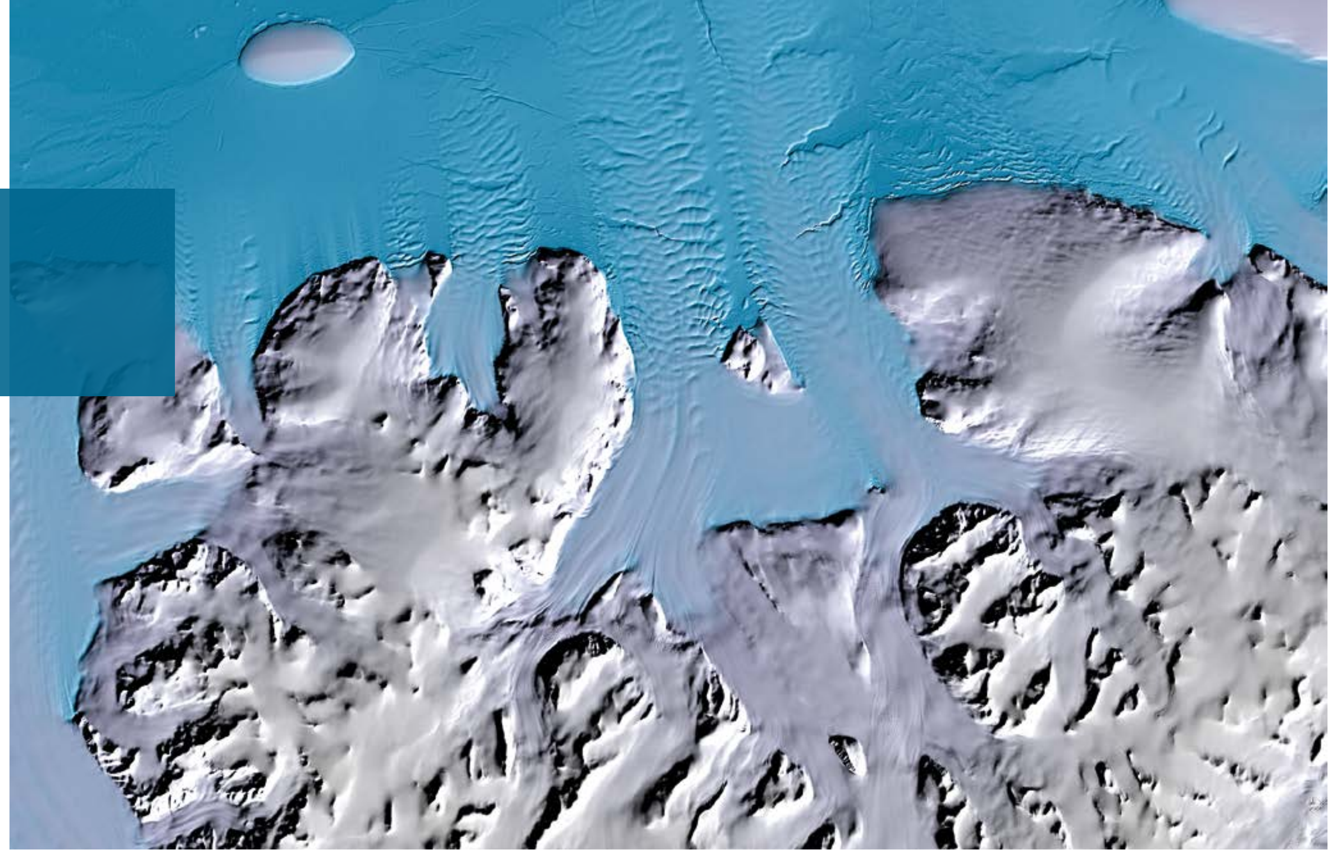
More than 97% of all generic (no forest, no ice) geocells are within the 2 m / 4 m specification of the relative height error

Summary of the absolute height accuracy, evaluated using the best (flattest footprint) 1000 ICESat validation points per DEM geocell. The achieved performance is provided for generic, ice, forest and all geocells

Statistics	Generic geocells	Ice geocells	Forest geocells	All geocells
Landmass [million km²]	96.68	14.31	33.22	144.21
Accumulated number of validation points (millions)	10.20	2.71	2.58	15.49
Mean height deviation of validation points [m]	0.04	-2.83	0.57	-0.37
Accumulated absolute height accuracy of 10 m (linear error)	99.84%	98.42%	99.17%	99.48%
Accumulated absolute height accuracy with 90% linear error [m]	0.88	6.37	2.33	3.49

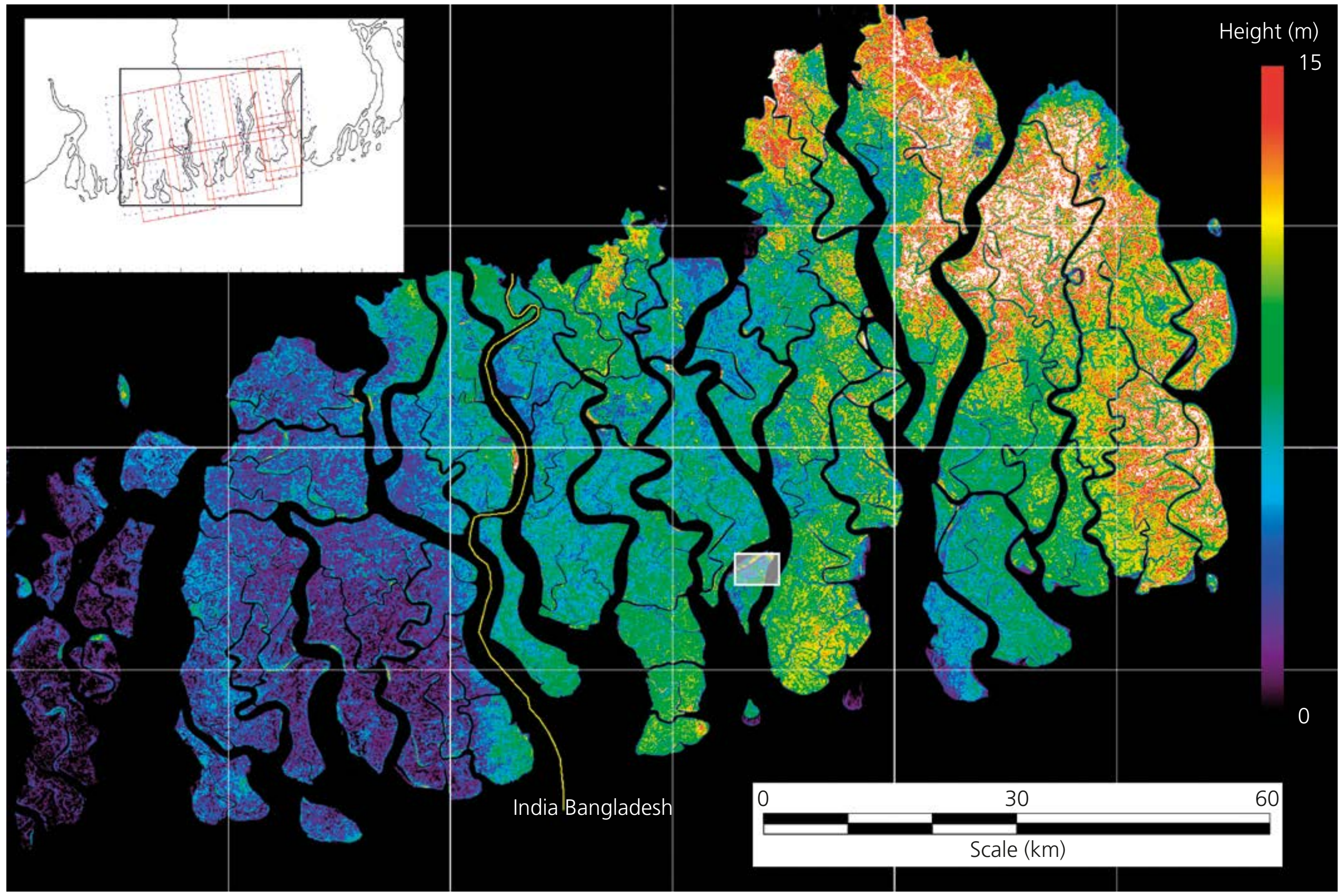
Scientific Exploitation and Selected Example Results

The scientific exploitation of TanDEM-X goes far beyond the DEM and the unique capabilities enable numerous secondary mission objectives based on along-track interferometry as well as new bistatic and multistatic SAR techniques. Several bistatic experiments were already conducted during the TanDEM-X commissioning phase. When the geometry was appropriate during the operational DEM phase, additional scientific data takes have been included into the timeline from the very beginning. After completion of the data acquisition for the global DEM, a dedicated science phase was introduced from 2014 to 2016 to exploit the unique features of the TanDEM-X mission. Large cross-track baselines of up to 4 km allowed for the acquisition of high-resolution DEMs and for polarimetric SAR interferometry experiments over agricultural fields. The science phase also included an along-track interferometry campaign, for which suitable baselines have been adjusted over test areas on the northern and southern hemisphere. To further improve the control accuracy of the satellite formation in along-track, the so-called TanDEM-X Autonomous Formation Flying (TAFF) system has been activated. For a few months the satellite twins flew at an along-track distance of 76 km (corresponding to about 10 s time lag) and operated in the pursuit monostatic mode. After the science phase, close formation flight was re-established in 2016 and has been kept until today. In the last years further experiments and demonstrations have been carried out without jeopardizing the operational data acquisition of the TanDEM-X mission.



TanDEM-X DEMs of glaciers in Antarctica are key to investigate melting processes

TanDEM-X Science



Picture: NASA

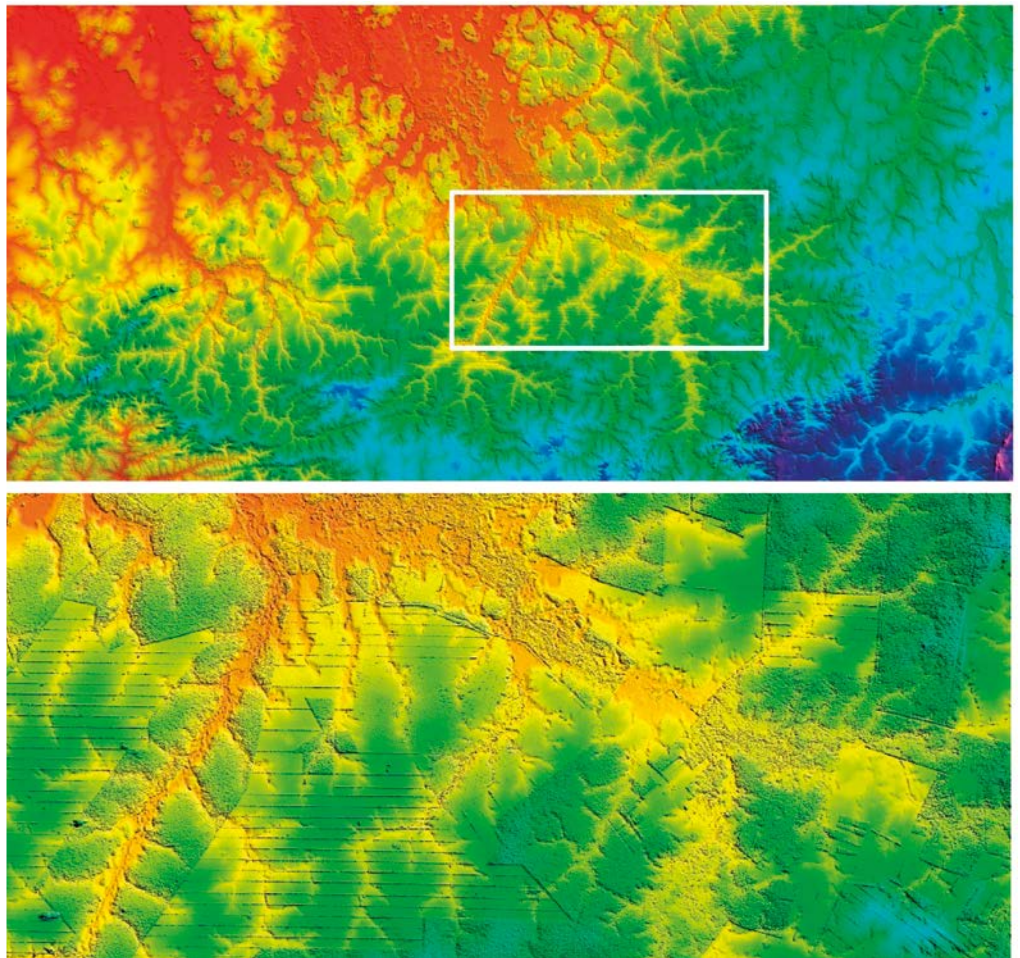
From TanDEM-X data derived canopy height of the largest mangrove forest, Sundarbans (India/Bangladesh).

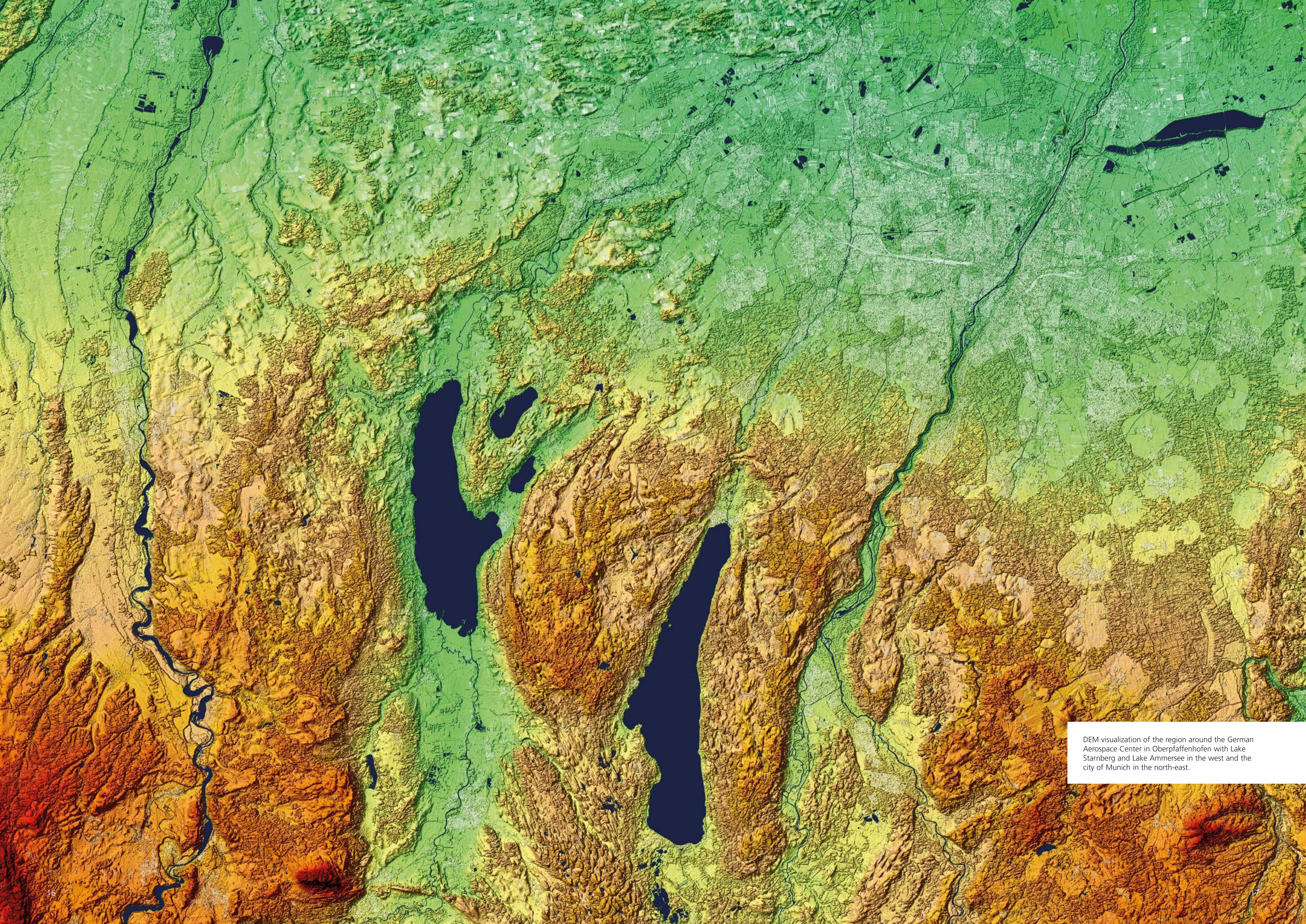
Among the innumerable demonstrations of new techniques and applications, the following examples summarize the potential of future bistatic and multistatic SAR missions as well as the high flexibility of the ground segment and of the radar instruments of both satellites: A) High-resolution digital elevation models based on multiple single-pass interferometric acquisitions; B) Polarimetric SAR interferometry and SAR tomography for tree height estimation; C) Along-track SAR imaging for ocean current velocity estimation; D) Bi-directional along-track interferometry for two-dimensional ocean current velocity estimation; E) Double differential Interferometry for crop height estimation; F) Digital Beamforming with four phase centers for ambiguity suppression; G) Pursuit monostatic along-track interferometry for ice floe rotation estimation; H) Boreal forest biomass estimation; I) Ship velocity and rotation estimation; J) Ice sheet penetration depth estimation and ice sheet classification; K) Bistatic imaging; L) Glacier height change due to ice melting; M) Permafrost disturbance and height changes; N) Sea ice height estimation and O) Two-Look TOPS interferometry for estimation of azimuth displacements.

Furthermore, throughout the mission selected super sites (e.g. outlet glaciers in Antarctica or Greenland) have been regularly observed. Such data sets are usually processed to Co-registered Single-look Slant-range Complex (CoSSC) products and provided to members of the science team for multi-temporal analyses. Such data were used, for example, to measure and report the dramatic ice loss for outlet glaciers on the polar ice caps as well as inland glaciers.

The TanDEM-X Science Team has been instrumental in utilizing, validating, and innovating TanDEM-X DEMs and other products, leading to many new scientific results and applications. Since 2011, invited sessions on TanDEM-X at IGARSS and EUSAR conferences have showcased these results.

TanDEM-X DEM of the rain forest at the border between Brazil and Bolivia (top) and enlargement showing typical deforestation patterns (bottom). Topographic heights are shown in different colors.





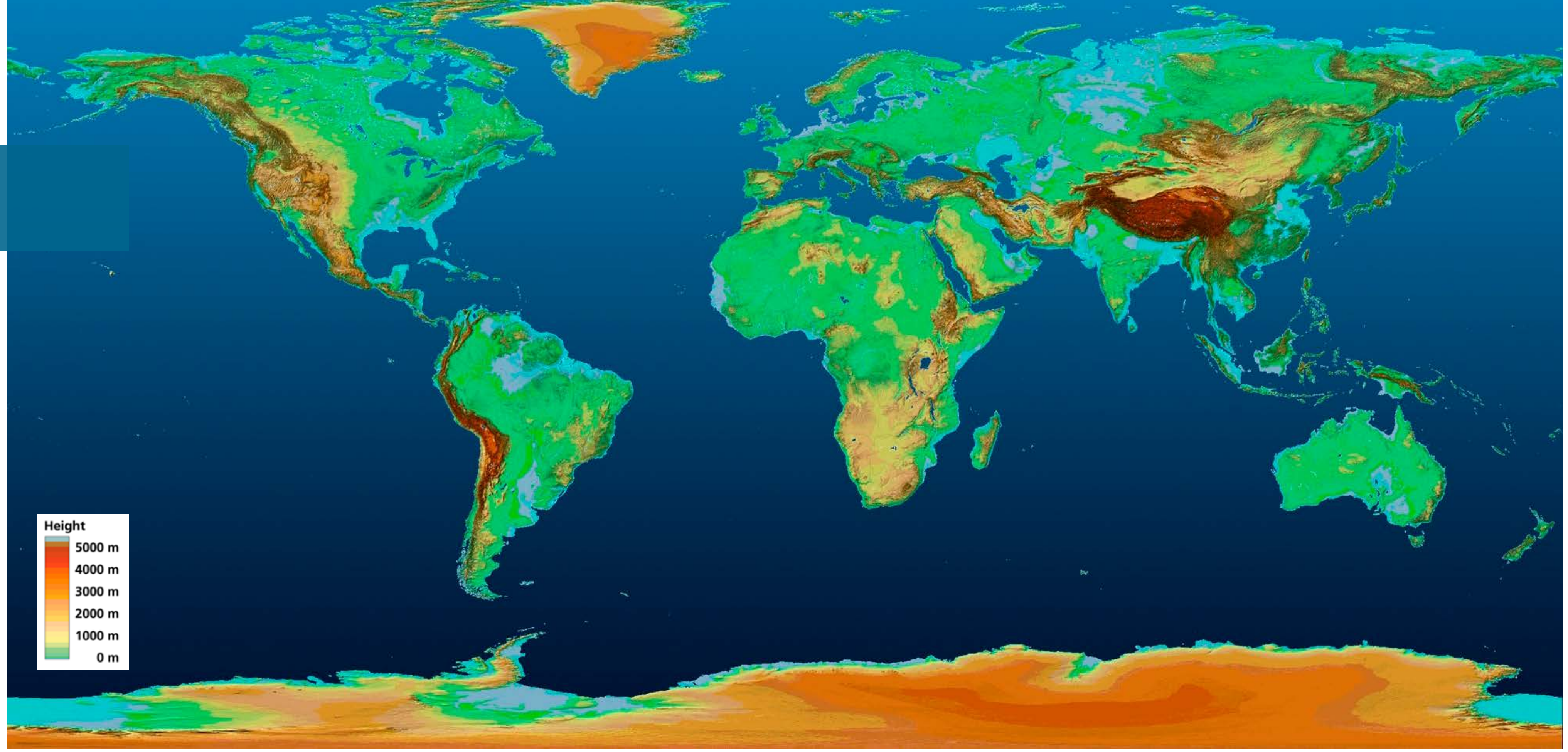
DEM visualization of the region around the German Aerospace Center in Oberpfaffenhofen with Lake Starnberg and Lake Ammersee in the west and the city of Munich in the north-east.

Products and Availability

TanDEM-X Global DEM (2016)

The TanDEM-X Global DEM is the nominal, non-edited product variant of the global Digital Elevation Model acquired between 2011 and 2014. It was the primary objective of the TanDEM-X mission and is available since 2016. The TanDEM-X Global DEM represents the reflective surface in X-Band, i.e. it is a digital surface model over vegetation but below the surface for ice and snow. It is partitioned in so-called geocells covering 1° x 1° in latitude and longitude at an independent grid spacing (posting) of 12m (0.4 arcseconds). The absolute height error is about one meter, the relative height is well within the 2m specification. It covers all Earth's landmasses from pole to pole with a completeness rate of 99.89%. Further variants at 30m (1 arcsecond) and 90m (3 arcseconds) grid spacing have been derived by averaging of the input 6m Raw-DEMs, resulting in a considerable reduction of the relative height error.

For scientific purposes the TanDEM-X Global DEM 2016 is accessible via the established proposal process at the DLR Science Coordination:**https://tandemx-science.dlr.de/**



Overview of the TanDEM-X Global DEM 2016

TanDEM-X Global DEM 2020

Between 2017 and 2020 the global landmasses have been acquired once more for an update of the global DEM. The TanDEM-X Global DEM 2020 is currently being processed and is expected to become available in 2024.

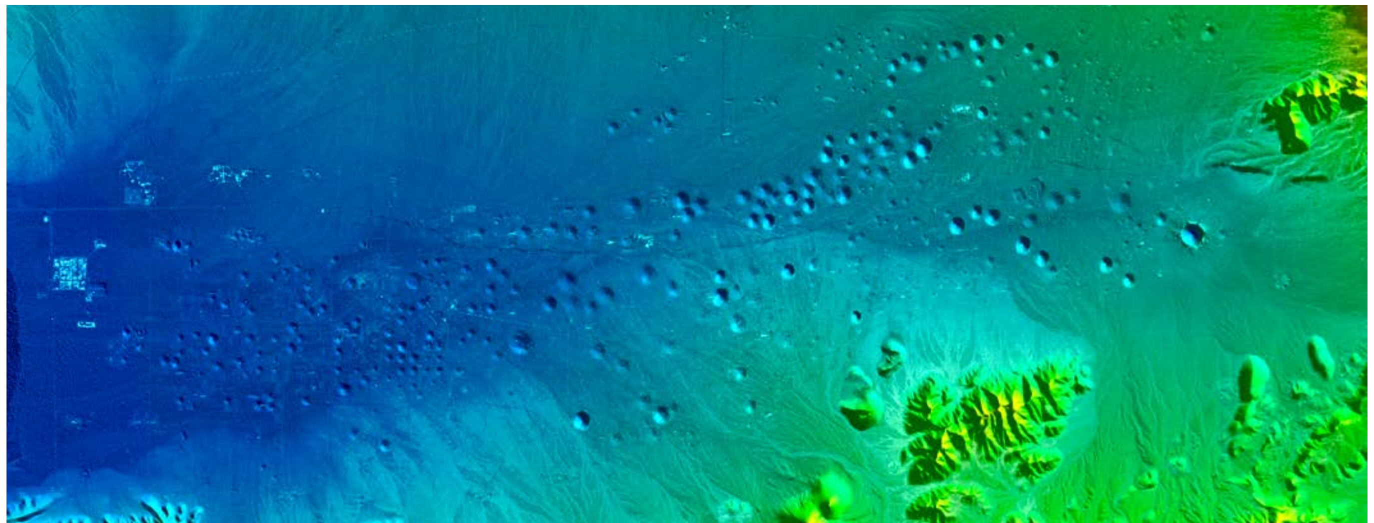
It will be accessible as the TanDEM-X Global DEM 2016: **https://tandemx-science.dlr.de/**

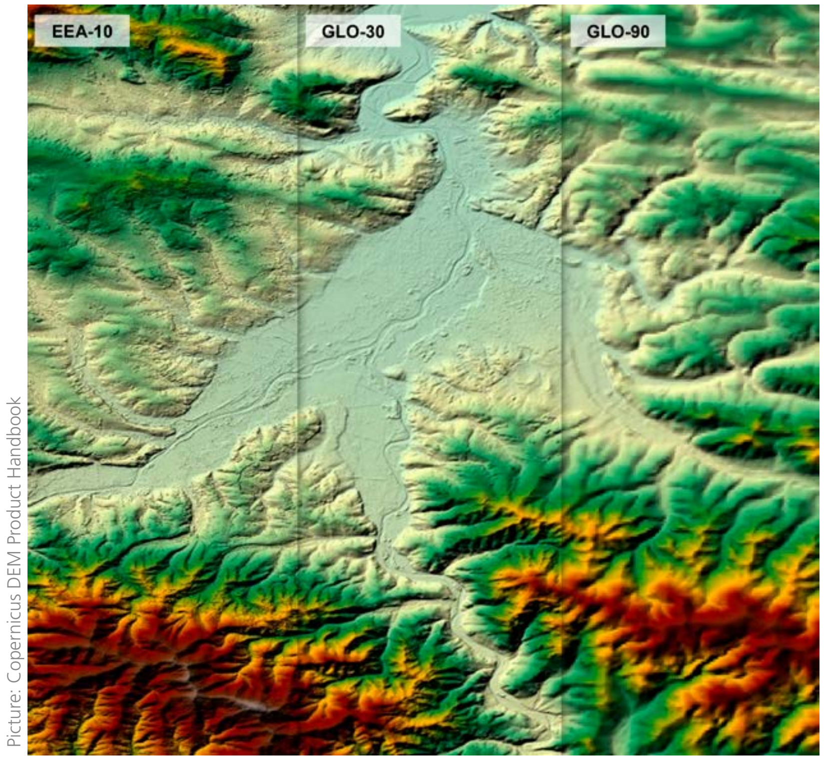
TanDEM-X DEMs for Commercial Users
WorldDEM™ and WorldDEM™ Neo

Airbus Defence and Space is responsible for the commercialization of TanDEM-X data. Their WorldDEM™, an edited digital surface model, is based on the TanDEM-X Global DEM 2016. The WorldDEM™ Neo product is an update of the WorldDEM™ based on Raw DEMs acquired between 2017 and 2021 featuring a 5m grid spacing. Beyond WorldDEM™ and WorldDEM™ Neo further thematic layers and derivatives are offered.

Commercial customers can purchase the data at:
https://www.intelligence-airbusds.com/imagery/reference-layers/worlddem/

DEM of the Nevada Nuclear Test Site, USA, which was used between 1951 and 1962 for on-ground and atmospheric nuclear tests detonations.





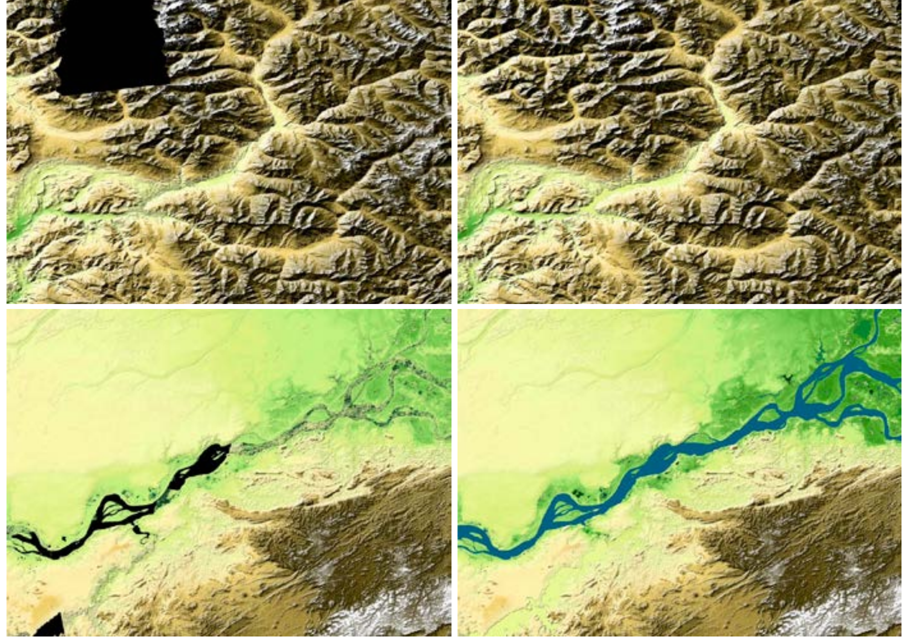
Picture: Copernicus DEM Product Handbook

Comparison of the resolution of different versions of the Copernicus DEM

Copernicus DEM

The Copernicus DEM was derived from Airbus Defence and Space's WorldDEM™, which in turn is based on the TanDEM-X Global DEM 2016. The Copernicus DEM is provided in three different variants, designated EEA-10, GLO-30, and GLO-90, corresponding to a grid spacing of 10m for Europe, 30m, and 90m for global coverage. Whereas GLO-90 (global) and GLO-30 (global except Armenia and Azerbaijan) are freely available, the EEA-10 is restricted to EU funded projects, EU institutions, Copernicus Services and Operators.

The Copernicus DEM can be obtained from ESA "Copernicus Contributing Missions Online": **https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model**



Examples for the DEM editing performed on the TanDEM-X Global DEM 2016. The upper images show the filling of gaps, while the lower ones present the flattening of water bodies like rivers.

TanDEM-X 30m Edited DEM

The Edited DEM with a grid spacing of 30m is based on the TanDEM-X Global DEM 2016. Isolated gaps in the coverage were filled by external reference data like local LiDAR DEMs, the NASA DEM or the ALOS DEM and water bodies were flattened. This editing was performed using a largely automated process. The TanDEM-X 30m Edited DEM is provided with different vertical reference systems, the WGS84-G1150 (ellipsoidal heights, TanDEM-X Global DEM reference) and the EGM2008 (geoid heights, Copernicus DEM reference).

For scientific purposes and after simple registration without proposal the TanDEM-X 30m Edited DEM is globally accessible at **https://geoservice.dlr.de/web/maps.**

The unedited TanDEM-X Global DEM 2016 at 90m posting, the so-called TanDEM-X 90m DEM, is also available on the same server since 2018. Due to the finer posting and editing it is recommended to replace the TanDEM X 90m DEM by the TanDEM-X 30m Edited DEM.

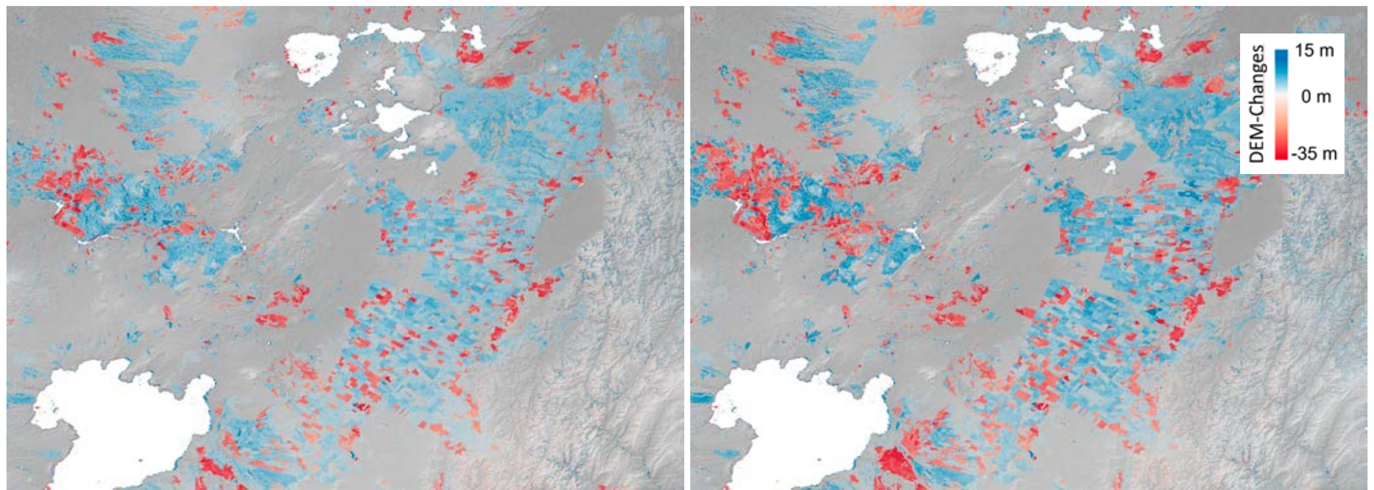
TanDEM-X
Products

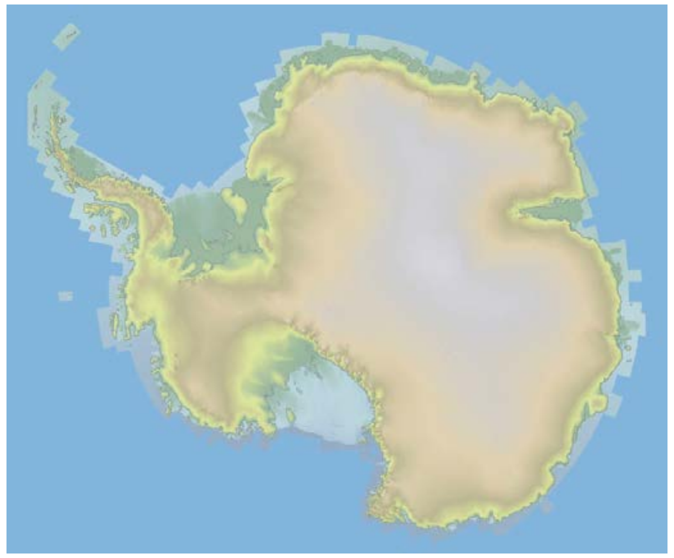
TanDEM-X 30m DEM Change Maps

The so-called TanDEM-X 30m DEM Change Maps provide the height difference of newly acquired data w.r.t. the TanDEM-X 30m Edited DEM as reference. Precise time tags for every single pixel of the DEM Change Maps enable detailed analyses on the dynamics of the Earth's surface topography. DEM Change Maps are also provided at a grid spacing of 30 m. In the first release the time frame is limited to 2016-2022. As TanDEM-X continues in the 4D Phase it is planned to gradually including new acquisitions and to build up stacks of DEM Change Maps.

For scientific purposes the TanDEM-X 30m DEM Change Maps are globally accessible at **https://geoservice.dlr.de/web/maps** after simple registration without proposal.

TanDEM-X 30m DEM Change Maps for data acquired in 2018 (left) and 2019 (right) over a managed forest near Lake Taupo in New Zealand revealing the changes in deforestation and regrowth.





Overview of Antarctica as provided by the Polar DEM 90 m, an edited version of Antarctica derived from the TanDEM-X Global DEM 2016.

TanDEM-X PolarDEM 90m

The TanDEM-X PolarDEM 90m of Antarctica is a gap-free and edited version of the TanDEM-X 90-m DEM. It is provided in Antarctic Polar Stereographic projection (EPSG:3031) with a grid spacing of 90 meters. The DEM elevation values represent ellipsoidal heights relative to the WGS84 ellipsoid. The majority of the data were acquired between April 2013 and October 2014.

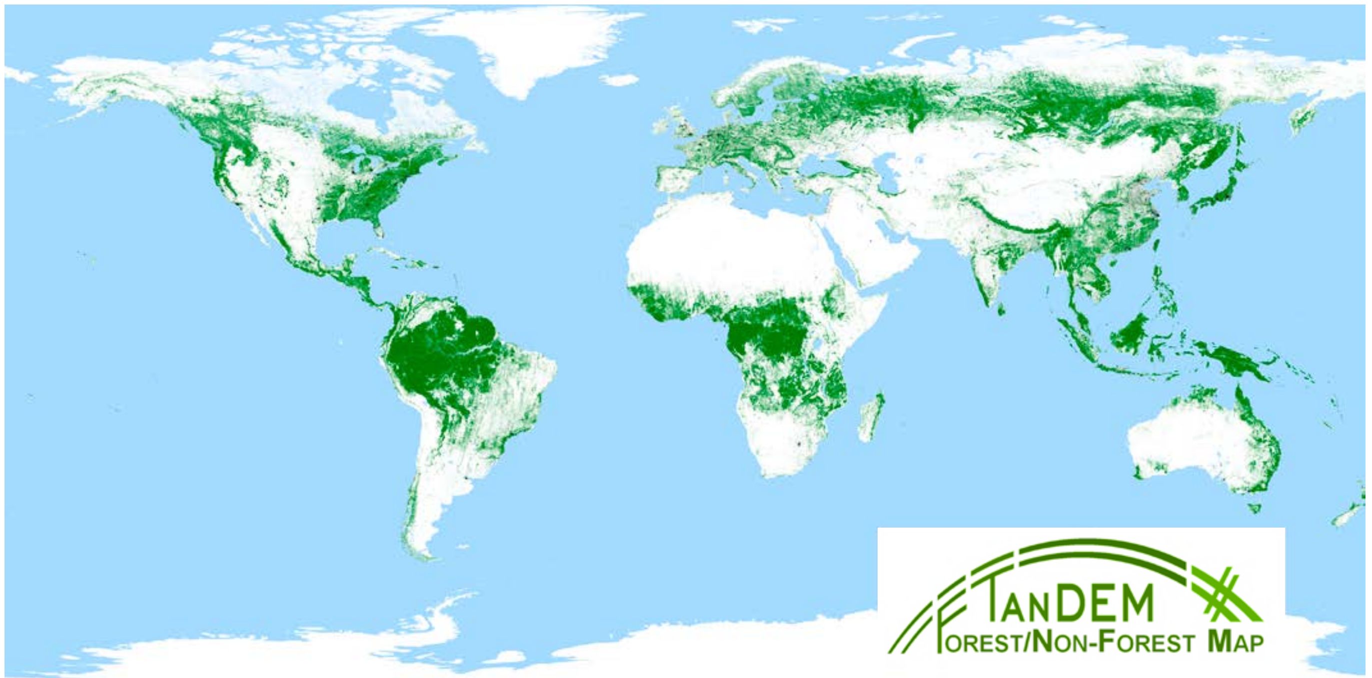
TanDEM-X PolarDEM 90 m is accessible for scientific purposes at:
https://geoservice.dlr.de/web/maps/tdm:polardem90:Antarctica

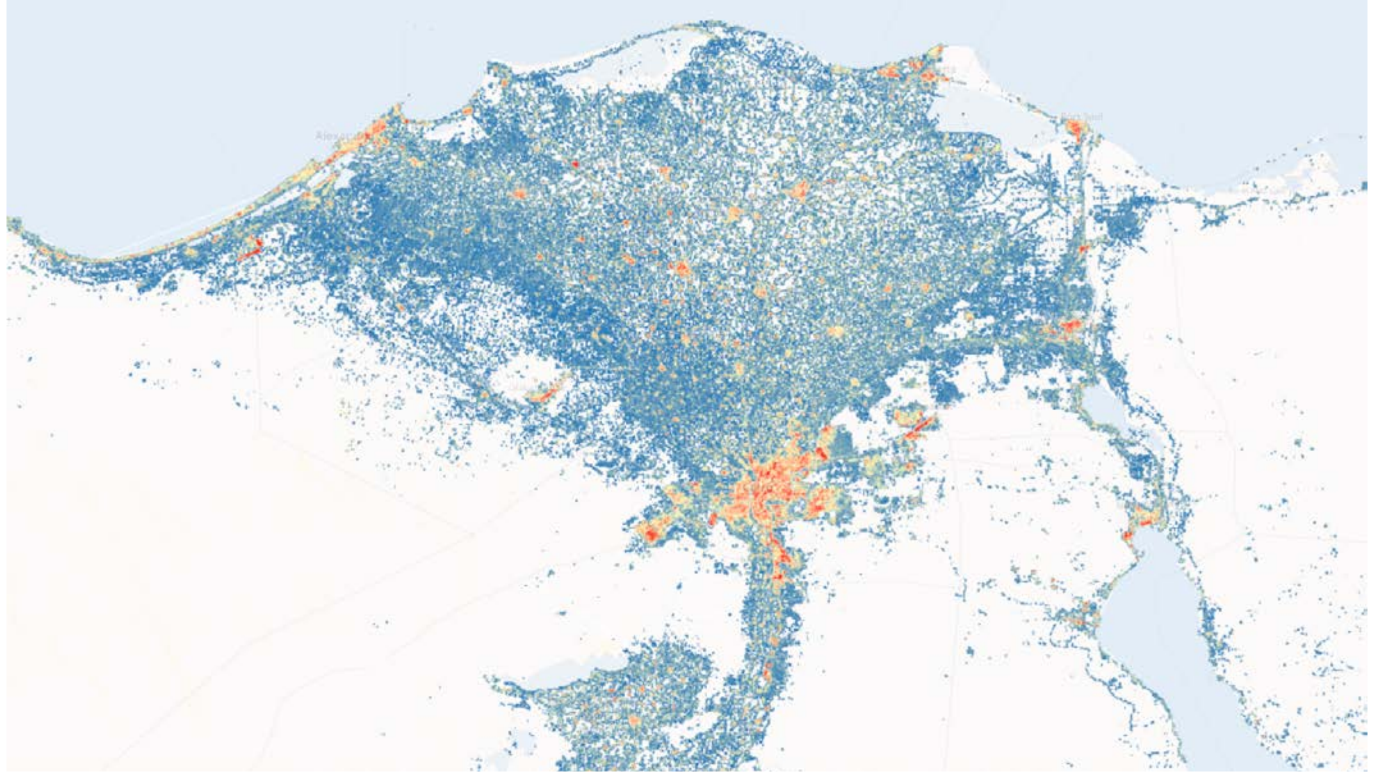
TanDEM-X Forest/Non-Forest Map

The TanDEM-X Forest/Non-Forest Map is a global forest/non-forest classification mosaic derived from the bistatic interferometric data acquired between 2011 and 2015 for the generation of the TanDEM-X Global DEM 2016. The global dataset of calibrated amplitude, bistatic coherence and elevation information at quicklook resolution of 50 m x 50 m has been used for the classification. In particular, the volume correlation factor is used as the main indicator for identifying vegetated areas. The TanDEM-X Forest/Non-Forest Map is essentially a binary map that indicates the presence of forest.

For scientific purposes the TanDEM-X Forest/Non-Forest Map is globally accessible at **https://geoservice.dlr.de/web/maps** after simple registration without proposal.

Global overview of the Forest/Non-Forest Map derived from quicklooks of the TanDEM-X Global DEM 2016





Example of the World Settlement Footprint 3D for the Nile delta in Egypt

World Settlement Footprint 3D

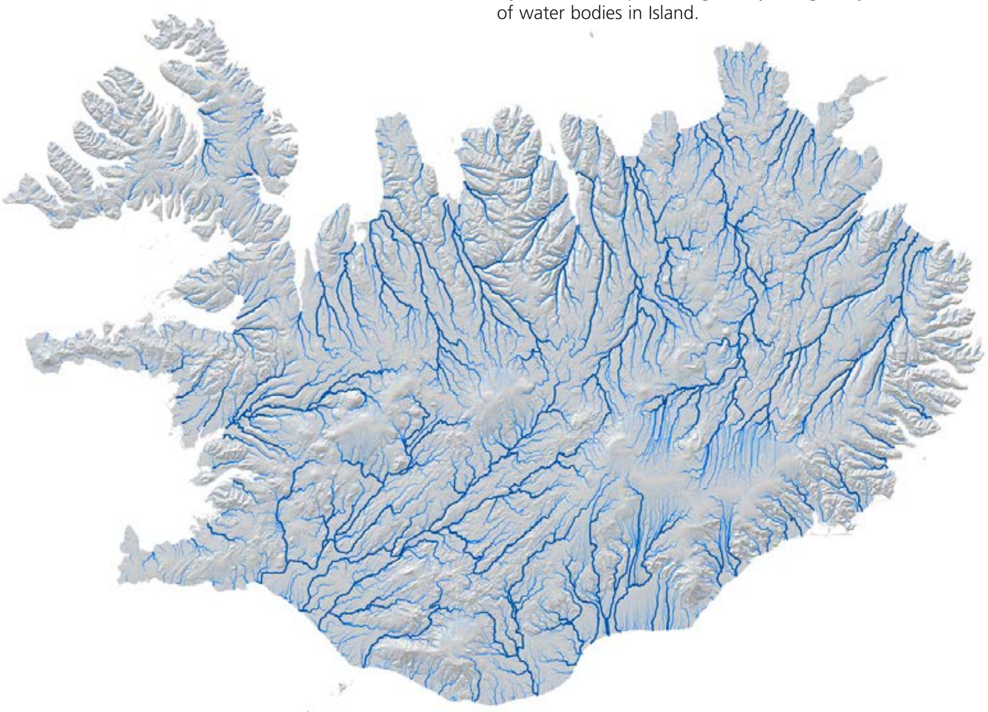
The World Settlement Footprint 3D dataset quantifies the proportion, total area, average height, and total volume of buildings for a measurement grid with a 90-m cell size. The World Settlement Footprint 3D is created using a modified version of the World Settlement Footprint mask for human settlements derived from Sentinel-1 and Sentinel-2 satellite imagery with a spatial resolution of 10 m, in combination with 12 m digital elevation data and radar imagery acquired by the TanDEM-X mission.

The World Settlement Footprint 3D is available at:
https://geoservice.dlr.de/web/maps/eoc:wsfevolution

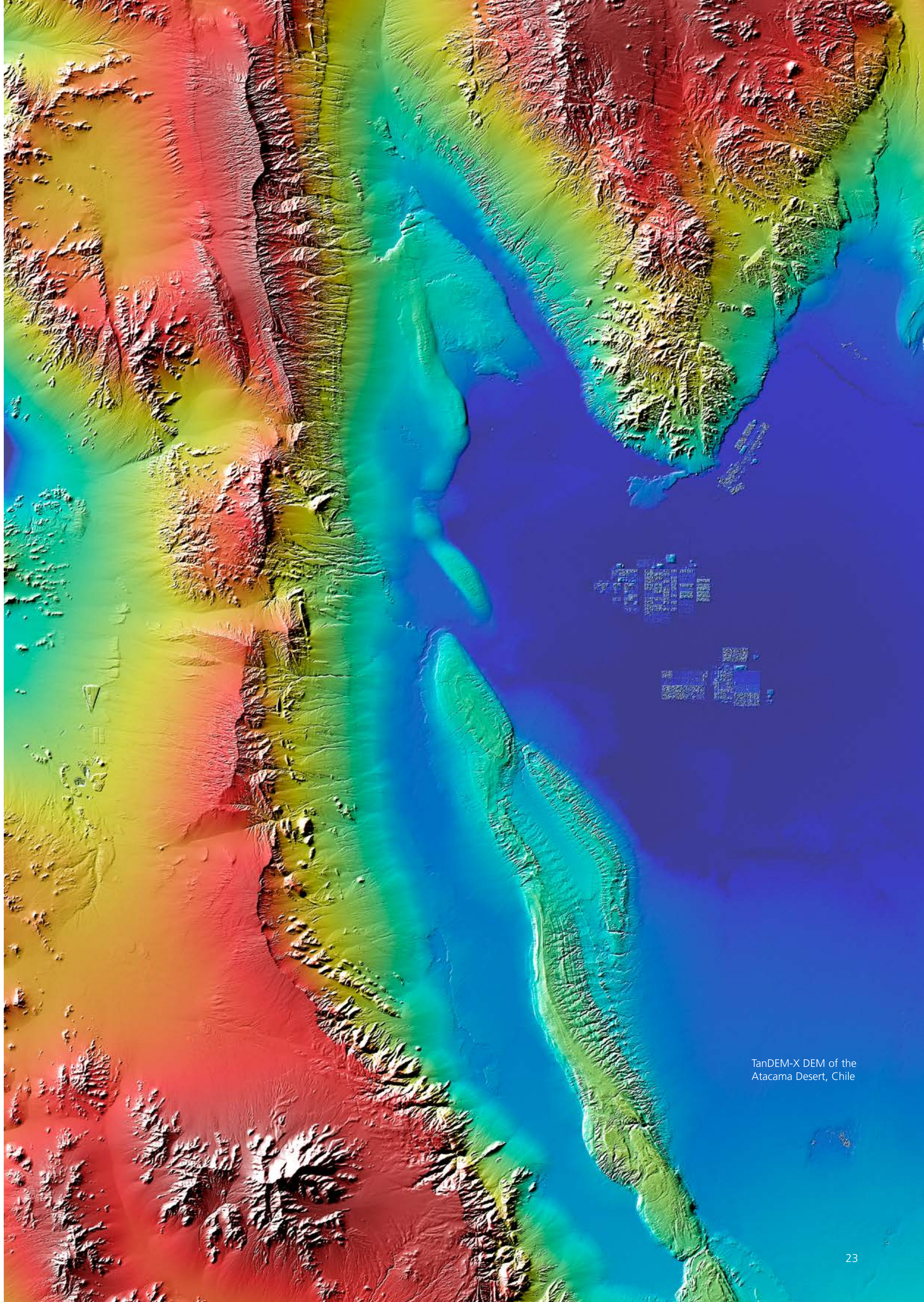
HydroSHEDS-X

The HydroSHEDS database provides digital hydrographic information that can be applied in Geographic Information Systems (GIS) or hydrological models at multiple scales, from local to global. The first version of HydroSHEDS introduced in 2008 was derived from the Shuttle Radar Topography Mission (SRTM). The new version HydroSHEDS-X is derived from the TanDEM-X data set in order to improve the quality at global coverage including the Arctic region.

HydroSHEDS products are available at:
https://www.hydrosheds.org/hydrosheds-core-downloads



HydroSHEDS map showing the hydrological system of water bodies in Island.



TanDEM-X DEM of the Atacama Desert, Chile

DLR at a glance

DLR is the Federal Republic of Germany's research centre for aeronautics and space. We conduct research and development activities in the fields of aeronautics, space, energy, transport, security and digitalisation. The German Space Agency at DLR plans and implements the national space programme on behalf of the federal government. Two DLR project management agencies oversee funding programmes and support knowledge transfer.

Climate, mobility and technology are changing globally. DLR uses the expertise of its 55 research institutes and facilities to develop solutions to these challenges. Our 10,000 employees share a mission – to explore Earth and space and develop technologies for a sustainable future. In doing so, DLR contributes to strengthening Germany's position as a prime location for research and industry.

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