TanDEM-X Mission Status

Christo Grigorov[1], Markus Bachmann[1], Johannes Böer[1], Thomas Kraus[1], Marie Lachaise[2], Manfred Zink[1]

[1]Microwaves and Radar Institute, German Aerospace Center (DLR), Germany

[2]Remote Sensing Technology Institute, German Aerospace Center (DLR), Germany

Christo.Grigorov@dlr.de

***Abstract* — In 2010 the first formation flying radar system was built by extending the TerraSAR-X synthetic aperture radar mission by a second, TerraSAR-X-like satellite called TanDEM-X. The resulting large single-pass radar interferometer features flexible baseline selection. This enables 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 with unprecedented accuracy – was achieved in 2016. Up to 2020 the mission acquired data for a global change layer (TanDEM-X DEM 2020) revealing the height changes relative to the first dataset. After so many years in orbit both spacecraft show aging effects. There are already several redundant units in operation on both satellites, but they are still fully functional and have enough consumables for several additional years. Repeated height measurements allow the observation and quantification of dynamic processes on the Earth's surface such as deforestation or melting of glaciers and ice sheets. Therefore, bistatic operations continue in the TanDEM-X 4D Phase with a focus on changes in the cryosphere, biosphere and densely populated areas and regions with larger height changes.**

***Keywords* — Synthetic aperture radar (SAR), Interferometry, Bistatic SAR, Digital elevation model (DEM).**

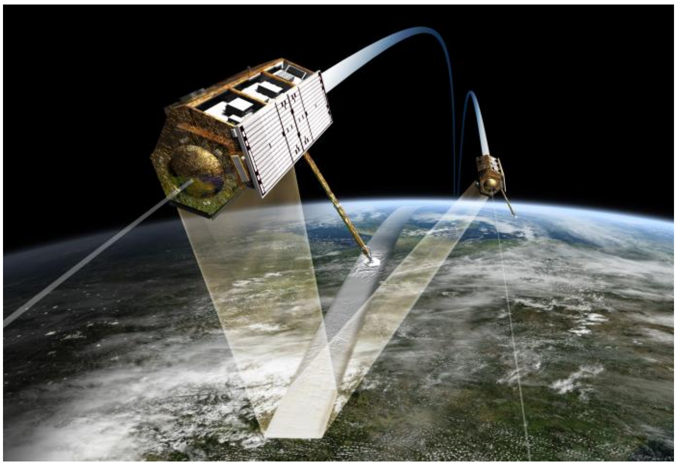

Fig. 1: The TanDEM-X radar interferometer comprises of two satellites and has been operational for more than 12 years already.

I. Mission Concept

The TanDEM-X mission comprises of two nearly identical radar spacecraft that form the first satellite-based synthetic aperture radar (SAR) interferometer in space as illustrated in Fig. 1 [1]. The first one, TerraSAR-X (TSX), was launched in 2007 and its twin brother, TanDEM-X (TDX), in 2010.

Each satellite is equipped with a high-resolution X-band active phased array antenna that is capable of acquiring data in several imaging modes [2]. These range from Staring Spotlight with an azimuth resolution of 0.25 m and a range extent of up to 7.5 km [3], up to six-beam wide ScanSAR with a resolution of 40 m and a range extent of over 200 km [4]. The SAR instruments are capable of acquiring in single and dual polarization (horizontal and/or vertical polarization) and by activating the dual receive antenna (DRA) mode in dedicated campaigns – also in quad polarization [5].

The imaging mode used for the global digital elevation model (DEM) acquisitions is Stripmap single polarization with a resolution of 3.3 m and a range extent of 30 km. Furthermore, the bistatic SAR interferometer is configured in a way that one of the satellites transmits radar pulses and both of them acquire the reflected signal from the ground (bistatic operation). Since the two radar systems use independent ultra-stable oscillators (USOs), a relative phase referencing is needed in order to eliminate oscillator related errors during the interferometric processing of the bistatic acquisitions [6]. For that purpose, a dedicated X-band intersatellite synchronization link has been established and is always used during bistatic operations. The signals exchanged via this link are then used for the generation of a compensation phase to correct the bistatic interferograms during processing.

The two satellites fly in close formation with a varying distance of, typically, a few hundred meters [1]. This enables the simultaneous acquisition of images with a well-defined cross-track baseline that can be used for single pass interferometry and therefore for highly accurate topographic mapping of the Earth surface. The dual satellite flight, a helix formation, is achieved by an out-of-plane displacement of the two orbits by different right ascensions of the ascending nodes (horizontal separation) and by different orbit eccentricity vectors (vertical separation). The chosen formation type provides for a two-fold benefit. It ensures that the orbits of the satellites never cross, which minimizes the collision risk and eliminates the need for an onboard autonomous control [7], [8]. The helix formation enables the safe variation of the distance between the satellites and therefore a variation of the geometry of the SAR interferometer as well.

II. TanDEM-X Global DEM

The primary goal of the mission has been the generation of a DEM with the following specification: absolute vertical accuracy of 10 m, relative height accuracy of 2 m for moderate slopes of up to 20% and 4 m for larger slopes and a spatial

https://ieeexplore.ieee.org/document/10289570

resolution of 12 m [1]. An acquisition strategy has been drawn up and implemented in order to cover all land masses of the Earth [9]. The strategy in essence represents a continuously optimized trade-off between the SAR system constraints (such as available acquisition time per orbit and downlink capacity) and the acquisition of enough data to enable the interferometric processing with the necessary quality. For that reason, two global coverages have been originally foreseen. Some critical areas have had to be acquired more often, either due to the nature of the land cover – for example over forests or deserts, or due to the necessity of having different acquisition geometry to overcome shadow and layover effects especially in mountainous regions.

The acquisitions for the global DEM have been completed in 2014 and the final product has been successfully generated in 2016 [10]. Thanks to the accurately calibrated system, the quality of the final DEMs is well within specifications [11]. The absolute height accuracy is in the order of 1 m, which means one order of magnitude below the 10 m requirement. The global coverage of the TanDEM-X DEM is also quite complete and features an exceptionally low percentage of void areas (global count of 0.1%).

III. TanDEM-X Scientific Exploration

Apart of the generation of a global DEM, the unique capabilities of TanDEM-X support applications based on along-track interferometry (ATI) and the demonstration and application of new SAR techniques, with a focus on multistatic SAR, polarimetric SAR interferometry, digital beamforming, and super resolution. Both radar instruments feature a very flexible commanding scheme, which in combination with the adjustable baseline geometries enables hitherto unprecedented capabilities for experimental modes and new techniques. Such acquisitions have been interleaved within the nominal DEM imaging from the very beginning of the mission [12], [13], [14], [15].

IV. TanDEM-X DEM 2020

The global TanDEM-X DEM clearly demonstrated that, given its outstanding accuracy, height differences are visible between interferometric SAR data acquired at different times. As a matter of fact, even small height changes are well detectable in the X-band DEM. Therefore, in 2017 it was decided to acquire an additional complete coverage of the Earth's landmass. The aim is to provide an independent DEM dataset representing a well-defined time span from September 2017 until mid-2020. This so-called TanDEM-X DEM 2020 will allow for an assessment of topographic changes with respect to the previous TanDEM-X DEM product on a global scale and will become available within the next year.

V. TanDEM-X 4D Phase

Analyses of topographic changes have revealed that the Earth’s surface is highly dynamic – changes in the height of glaciers, permafrost areas and forests have been expected, but changes due to agricultural activities and infrastructure projects also leave clear traces and can be measured. By repeatedly observing certain areas, a time series of data is created. The dataset gradually grows and, in addition to the three spatial dimensions, goes on to have a fourth dimension, time, revealing new, previously hidden findings. While the TanDEM-X DEM 2020 data set allows a one-time comparison between two time periods and, in a sense, is a snapshot of events on a global level, repeated recordings of particular focus areas give a more detailed picture. For example, the growth and degradation of forests can be measured as shown by the TanDEM-X DEM Change Maps in Fig. 2. Repeated height measurements also allow the observation and quantification of the melting of glaciers and ice sheets caused by global warming. The initial DEM change map products will be generated from the same acquisitions as for the TanDEM-X DEM 2020 and the time series products will be further extended during the 4D phase.

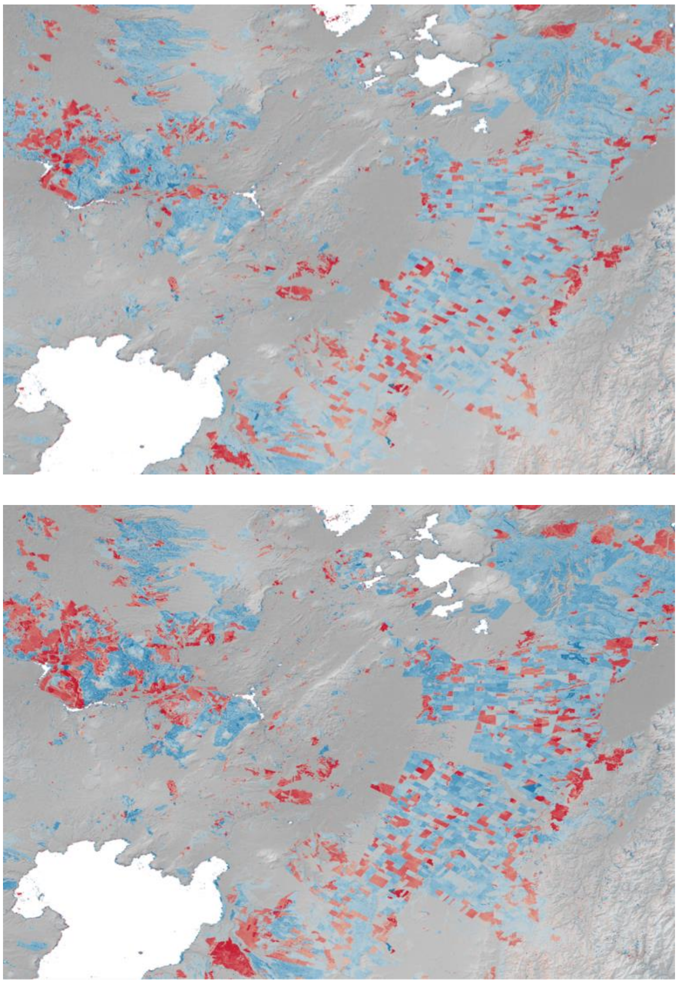

Fig. 2: TanDEM-X DEM Change Maps for an area east of Lake Taupo on New Zealand’s North Island showing the change in elevation with respect to the global TanDEM-X DEM for data recorded in 2018 (top) and 2019 (bottom). Changes concentrate on an intensively managed forest, where the elevation has decreased in the areas marked in red by up to 35 m due to logging, but significant growth, in the order of several metres, can be seen in the blue areas. The comparison of the two maps (2019 versus 2018) shows a significant increase in red areas due to advancing logging but also slightly darker blue tones in 2019 indicating growth. The preserved natural forest in the lower right corner is mature and stable and does not show any height changes.

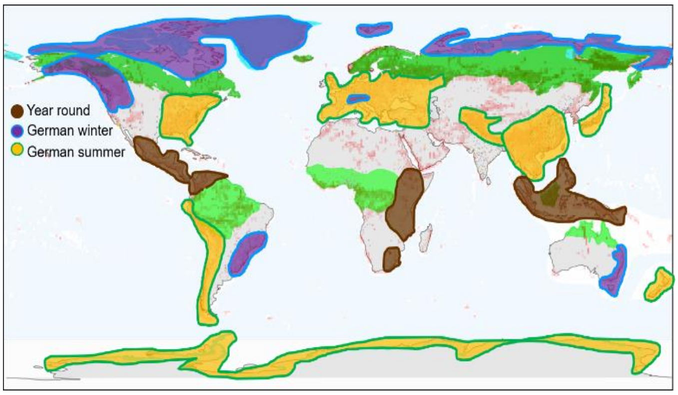

Fig. 3: Combined areas of interest for the TanDEM-X 4D Phase. The underlying red areas indicate regions of larger height change that will be further monitored by TanDEM-X. They are subdivided into three areas depending on the seasonality: purple areas are planned to be acquired during the winter period in the Northern Hemisphere; orange areas are planned during the summer in the Northern Hemisphere and the brown areas are acquired all year round. The green (forest) and blue (glaciers, permafrost) areas that serve scientific applications are alternated with the purple/yellow/brown areas from year to year.

The acquisition plan for the TanDEM-X 4D phase foresees the continuous coverage of the change regions along with further acquisitions for scientific applications. A global layout of both maps of interest is given in Fig. 3. In contrast to the global DEM phase when all satellite resources dedicated to the mission have still been available, the ageing of the satellites represent an additional challenge. The flown formations for the TanDEM-X 4D phase have been optimized in a way to make use of the natural drift of the satellite orbits and thus to preserve as much fuel as possible in order to increase the satellite life time. The coverage of wide areas benefits from long acquisitions, which due to the ageing of the on-board batteries cannot be performed anymore without severe battery degradation. Nevertheless, the careful distribution of shorter data takes does not significantly impact the duration of the acquisition plan and allows for an improved battery recovery between the data takes.

VI. Satellite Status

Both satellites have been designed for a lifetime of 5.5 years, which has been exceeded more than 10 and 7 years ago for the TSX and TDX, respectively. The quality of the acquired SAR images continues to be outstanding and well within the product specifications. In order to keep track of the SAR system status and to react to negative trends in the SAR performance the mission has established a long-term system monitoring (LTSM) process [16].

A. Ultra-Stable Oscillators

After so many years in orbit both spacecraft show aging effects. There are already several redundant units in operation on both satellites. One of these units is the USO, an essential part of the radar instrument. In November 2022 the redundant USO on the TSX satellite showed anomalies that had not been observed before. The internal heater control could not stabilize the USO operating temperature anymore and the resulting output radar frequency experienced continuous instabilities. These were visible in one of the LTSM parameters: the difference of the sampling frequency of the analogue-to-digital converters (ADCs) as shown for early November in Fig. 4. This difference is estimated from the radar pulses exchanged by the satellites on the X-band intersatellite synchronization link during SAR imaging. The ADC frequency is a good indicator for issues with the USO output frequency since it is directly derived from it. In order to bring the USO box temperature closer to its usual operational levels, the heaters of the surrounding radar frequency electronics box were switched on permanently. That reduced the daily frequency variations significantly but did not completely eliminated all drifts. However, a strong correlation between the USO frequency and the temperature has been observed that enabled the derivation of frequency correction polynomials. Their application showed that the estimated delta ADC frequency was corresponding very well with the measurements from the bistatic acquisitions.

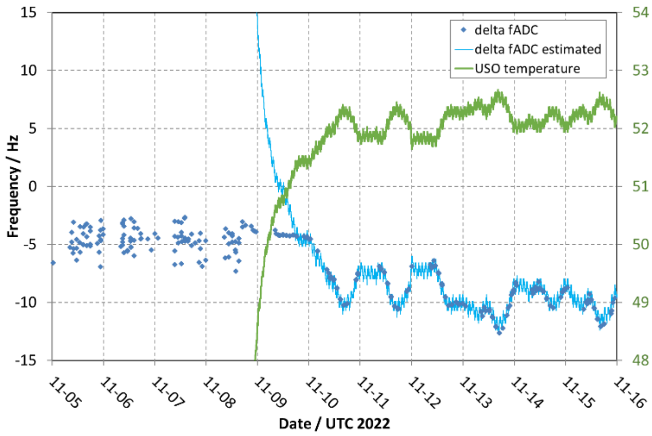

Fig. 4: The delta ADC frequency is used to monitor the relative frequency drift between the USOs of the two radar systems. The dark blue dots represent real measurements obtained from bistatic acquisitions. The green curve depicts the measured temperature of the TSX redundant USO electronics box. The light blue curve represents the estimated delta ADC frequency after applying temperature drift compensation – it corresponds very well with the dark blue measurement results.

B. Battery

The two satellites are already one of the oldest ones flying in space that carry lithium ion batteries on board. Fig. 5 shows that both batteries are in a much better condition as initially predicted. Still, their ageing is clearly visible – their capacities are at the moment down to about 60%. Other effects affecting the battery operations such as the diffusion rate limitation [17] have been discovered in the last years as well. In order to reduce the negative effects of the battery ageing, the maximum data take duration has been carefully managed. The original constraint of 400 s of continuous active operation has been gradually reduced since 2017 to about 60 s and 90 s for the TSX and TDX respectively. Moreover, during eclipse, when the satellites are not illuminated by the sun, the limits are further reduced to 35 s and 55 s. There is, however, still no need to adjust the total active acquisition time per orbit. The battery management along with the aim to prolong the mission duration via fuel-saving operations add an additional degree of complexity to the observation plan for the coming years of the TanDEM-X mission.

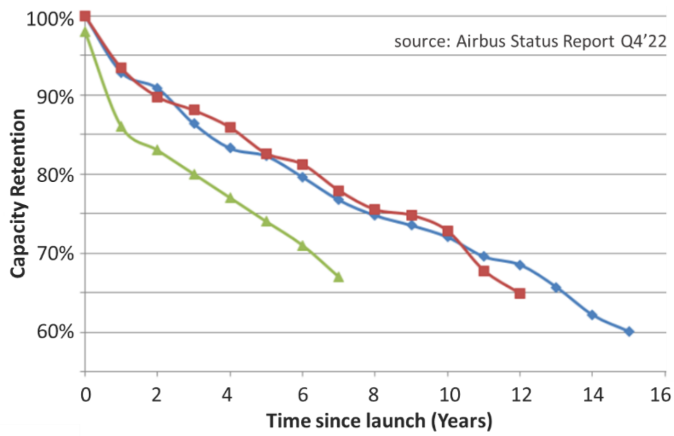

Fig. 5: Estimated versus predicted battery capacity retention. Dedicated battery capacity estimation tests are performed each year. The green curve depicts the prediction while the blue and the red ones represent the TSX and TDX battery estimations respectively.

VII. Conclusion

After almost 13 years of successful bistatic operation, TanDEM-X remains unique worldwide and continues to provide new insights into our changing Earth. The accurate topographic information is fundamental for essentially all Earth science disciplines. Being the basis of the Copernicus DEM [18], TanDEM-X fulfils all prerequisites to become the new topographic standard, thus advancing the success story of its predecessor, the Shuttle Radar Topography Mission.

The quality of the global DEM generated by TanDEM-X is unsurpassed and enables in the current 4D Phase the detection of height changes down to the meter range. The first results show a highly dynamic Earth surface with, e.g., melting glaciers and ice sheets, deforestation in tropical forests or mining activities. Capturing these dynamic processes has not been originally planned, but further enhances the value of the TanDEM-X mission the longer it remains operational.

After 16 and 13 years in space, the radar satellites TerraSAR-X and TanDEM-X are still fully functional and absolutely stable. They continue to deliver reliable, high quality radar data. At the moment their fuel reserves and battery capacities are expected to allow the continuation of the TanDEM-X mission for several more years without serious limitations.

References

[1] G. Krieger, A. Moreira, H. Fiedler, I. Hajnsek, M. Werner, M. Younis, M. Zink, “TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry,” in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 11, pp. 3317-3341, 2007.

[2] R. Werninghaus and S. Buckreuss, "The TerraSAR-X Mission and System Design," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, no. 2, pp. 606-614, Feb. 2010, doi: 10.1109/TGRS.2009.2031062.

[3] T. Kraus, B. Bräutigam, J. Mittermayer, S. Wollstadt and C. Grigorov, "TerraSAR-X Staring Spotlight Mode Optimization and Global Performance Predictions," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 9, no. 3, pp. 1015-1027, March 2016, doi: 10.1109/JSTARS.2015.2431821.

[4] U. Steinbrecher, T. Kraus, G. Castellanos Alfonzo, C. Grigorov, D. Schulze, B. Bräutigam, "TerraSAR-X: Design of the new operational WideScanSAR mode," *EUSAR 2014; 10th European Conference on Synthetic Aperture Radar*, Berlin, Germany, 2014, pp. 1-4.

[5] M. Gabele and M. Younis, "TerraSAR-X dual receive antenna mode: Experimental data results on azimuth ambiguity suppression and GMTI," *2009 European Microwave Conference (EuMC)*, Rome, Italy, 2009, pp. 966-969, doi: 10.23919/EUMC.2009.5296570.

[6] M. Younis, R. Metzig, G. Krieger, “Performance Prediction of a Phase Synchronization Link for Bistatic SAR,” in *IEEE Geoscience and Remote Sensing Letters*, vol. 3, pp. 429- 433, 2006.

[7] O. Montenbruck, R. Kahle, S. D’Amico, J.-S. Ardaens, “Navigation and Control of the TanDEM-X Formation”, in *Journal of Astronautical Sciences*, Vol. 56, no. 3, pp. 341–357, 2008

[8] R. Kahle, B. Schlepp, F. Meissner, M. Kirschner, R. Kiehling, “The TerraSAR-X / TanDEM-X Formation Acquisition – From Planning to Realization,” in *Journal of Astronautical Sciences*, vol. 59, pp. 564–584, 2012.

[9] M. Bachmann, T. Kraus, A. Bojarski, M. Schandri, J. Böer, T. E. Busche, J. Bueso Bello, C. Grigorov, U. Steinbrecher, S. Buckreuss, G. Krieger, M. Zink, "The TanDEM-X Mission Phases—Ten Years of Bistatic Acquisition and Formation Planning," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 14, pp. 3504-3518, 2021, doi: 10.1109/JSTARS.2021.3065446.

[10] M. Zink, A. Moreira, I. Hajnsek, P. Rizzoli, M. Bachmann, R. Kahle, T. Fritz, M. Huber, G. Krieger, M. Lachaise, M. Martone, E. Maurer, B. Wessel, "TanDEM-X: 10 Years of Formation Flying Bistatic SAR Interferometry," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 14, pp. 3546-3565, 2021, doi: 10.1109/JSTARS.2021.3062286.

[11] P. Rizzoli, M. Martone, C. Gonzalez, C. Wecklich, D. Borla Tridon, B. Bräutigam, M. Bachmann, D. Schulze, T. Fritz, M. Huber, B. Wessel, G. Krieger, M. Zink, A. Moreira, “Generation and Performance Assessment of the Global TanDEM-X Digital Elevation Model,” in *ISPRS Journal of Photogrammetry and Remote Sensing,* vol. 73, pp. 119-139, 2017.

[12] M. Pinheiro, A. Reigber, A. Moreira, “Large-Baseline InSAR for Precise Topographic Mapping: a Framework for TanDEM-X Large-Baseline Data,” *Advances in Radio Sci.*, pp. 231-241, 2017.

[13] F. Kugler, D. Schulze, I. Hajnsek, H. Pretzsch, K. P. Papathanassiou, “TanDEM-X Pol-InSAR performance for forest height estimation,” in *IEEE Transactions on Geoscience and Remote Sensing*, 52(10), pp. 6404-6422, 2014.

[14] M. Nannini, M. Martone, P. Rizzoli, P. Prats Iraola, M. Rodríguez Cassolà, A. Moreira, “Spaceborne Demonstration of Coherent SAR Tomography for Future Companion Satellite SAR Missions,” Proc. IGARSS, Fort Worth, USA, Jul./Aug. 2017.

[15] A. Alonso-González, H. Joerg, K. Papathanassiou, I. Hajnsek, “Dual-polarimetric agricultural change analysis of long baseline TanDEM-X time series data,” in *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 325-328.

[16] A. Bojarski, M. Bachmann, J. Böer, T. Kraus, C. Wecklich, U. Steinbrecher, N. Tous Ramon, K. Schmidt, P. Klenk, C. Grigorov, M. Schwerdt, M. Zink, "TanDEM-X Long-Term System Performance After 10 Years of Operation," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 14, pp. 2522-2534, 2021, doi: 10.1109/JSTARS.2021.3055546.

[17] F. Stathopoulos, K. Müller, M. Lino, T. Kraus, P. Klenk and U. Steinbrecher, "Operational Optimization of the Lithium-Ion Batteries of TerraSAR-X/TanDEM-X," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 14, pp. 3243-3250, 2021, doi: 10.1109/JSTARS.2021.3056174.

[18] (2023) The Copernicus DEM Website. [Online]. Available: https://spacedata.copernicus.eu/de/collections/copernicus-digital-elevation-model