Building a unified elevation data analysis tool in the frame of the CO3D mission

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Keywords: Digital Elevation Models, Quality control, Elevation data, Open source software, Satellite image analysis

Abstract

The CO3D mission, launched in July 2025, aims to reconstruct the Earth's continental surfaces in 3D. Assessing the quality of the resulting digital surface model requires an inter elevation data comparison tool, leading CNES to collaborate with the GlacioHack collective and join the governance of their open-source software xDEM. Originally developed for glacier research, xDEM offered valuable features for 3D data analysis, including 3D coregistration and uncertainty analysis. Recognizing its potential, CNES strategically chose to contribute to xDEM rather than maintain its own tool, demcompare. The main contributions include improvements in scalability, visualization, and ease of use. This collaboration has created a more robust tool that benefits both the CO3D mission and the broader scientific community. By combining resources and expertise, the project demonstrates how open-source development can drive innovation while reducing duplication of effort.

1. Introduction

The CO3D mission, successfully launched in July 2025 aboard the Vega-C rocket, represents a significant step towards the three-dimensional reconstruction of Earth's continental surface at high-resolution. This mission aims to produce a global one-meter Digital Surface Model (DSM) in less than four years using two pairs of optical satellites. The resulting DSM will address diverse civil and military needs. For civil applications, elevation data is essential for natural risk management—including floods (Bennani et al., 2019), landslides (Dai et al., 2024) or earthquake (Hummer et al., 2024)—as well as environmental monitoring, such as glacier mass changes (Berthier et al., 2024), snowpack evolution (Deschamps-Berger et al., 2020) or cliff face erosion (Letortu et al., 2020). On the military side, these models support operational planning, trafficability analysis, and low-altitude flight preparation.

Each CO3D satellite is equipped with commercial-off-the-shelf matrix sensors delivering a spatial resolution of 50 cm across four bands: visible (red, green and blue) and near-infrared bands. While each sensor's ground footprint measures approximately $7 \times 5\ km^2$, the satellites' agility enables the acquisition of $500\ km^2$ surfaces in a single pass, optimizing both coverage and mission efficiency. Using pairs of synchronous satellite images, a DSM at one-meter Ground Sampling Distance (GSD) is generated through processing with the open source photogrammetry software CARS[1] (Youssefi et al., 2020), integrated into the operational image chain (Lebègue et al., 2020).

Two levels of 3D products are available:

- L3 products, dedicated to specific productions of limited size (less than $50\ km \times 50\ km$);
- L4 products, which consist of $0.25^\circ \times 0.25^\circ$ tiles covering the entire planet in accordance with the defense gridded elevation data format[2] imposed by the mission. At the equator, the tile size reaches its maximum of approximately $27.75 \times 27.75\ km^2$.

A margin is always added to ensure consistency between adjacent L4 products (Lebègue et al., 2020). Therefore, the advantage of L4 products lies in its global coverage and consistency between tiles.

The primary objective of the CO3D mission is to achieve one-meter relative vertical accuracy for moderate slopes (less than 5%) and four-meter absolute vertical accuracy. Currently, few global Digital Elevation Model (DEM)s achieve this level of precision. Notable exceptions include WorldDEM Neo[3], which utilizes satellite imagery and interferometric elevation data from the TanDEM-X mission (2017-2021) to achieve five-meter GSD with two-meter relative and around one-meter absolute vertical accuracy. However, the methodology used to qualify this vertical accuracy is not well defined. Another example is EarthDEM[4], constructed from stereo images of Maxar satellites (WorldView-1, WorldView-2, WorldView-3, and GeoEye-1) acquired between 2009 and today. DEMs are distributed at

[1] CARS: `https://doi.org/10.5281/zenodo.17406459`

[2] DGED format: `https://dgiwg.org/documents/dgiwg-standards`

[3] WorldDEM Neo Technical Product Description: `https://elevation.oneatlas.airbus.com/assets/product-description/WorldDEM_Neo_DSM.pdf`

[4] EarthDEM Technical Product Specification: `https://earth.esa.int/eogateway/documents/20142/37627/WorldDEM-Technical-Specification.pdf`

a two-meter GSD using the open source photogrammetry software Surface Extraction from TIN-based Searchspace Minimization (SETSM). The accuracy of SETSM DEMs was evaluated in (Noh and Howat, 2015) and without ground control points, absolute accuracy is approximately two meters in both horizontal and vertical planes. However, its absolute horizontal and vertical accuracy specifications have not yet been verified. Therefore, for the CO3D mission, assessing the quality of the CO3D 3D products was deemed crucial. Yet, at the time of the mission preparation, there were no dedicated tools available for DEM accuracy assessment in the state-of-the-art.

This paper presents the steps that led CNES to collaborate with and join the governance of the open source software xDEM[5] for its DEM quality assessment. Initially, to address this gap for the CO3D mission, a generic, open source tool, reusable for future missions, was proposed, and CNES started the development of its own tool, demcompare. As the open source landscape evolved, the CNES contacted and merged efforts with xDEM. Although xDEM was not specifically designed for quality assessment, it possessed the generic methodological tools for 3D coregistration and uncertainty quantification to perform an accuracy assessment of DEMs. However, it required improvements in scalability, visualization and ease-of-use, which led to new developments. Eventually, to verify the quality of the DEM produced, xDEM was integrated into the image calibration center environment, facilitating a rigorous and automated evaluation of the quality of 3D model produced by the CO3D mission.

2. Towards a unified tool: xDEM

During the specification phase of the CO3D mission, there was a need to develop a software tool that could validate the 3D products. The primary objective was to statistically compare the CO3D 3D data against reference ground truth data to assess absolute accuracy. Additionally, the tool needed to enable comparisons between two CO3D 3D models to determine relative accuracy. At that time, no existing state-of-the-art software met these requirements.

2.1 History of demcompare

Consequently, the CNES developed the tool demcompare from scratch. The main goal was to integrate this tool into the image calibration center for automated DEM qualification during the CO3D 3D product qualification phase. Demcompare comprises several sequential steps:

1. aligning them (coregistration),
2. computing differences between the DEM,
3. deriving statistics from these differences,
4. and finally, printing all the results in a PDF file.

The coregistration step is crucial for DEM qualification, ensuring that observed differences are due to production errors rather than alignment artifacts. Its usage was primarily limited to comparing two DEMs.

[5] xDEM: `https://doi.org/10.5281/zenodo.4809697`

2.2 History of xDEM

Around the same period, xDEM was being developed. The xDEM[6] effort was created by the GlacioHack collective—a group of glaciology researchers working primarily with elevation data. The objective was to support a wide range of elevation analysis tools, particularly to modernize and improve older existing Python tools for DEM coregistration such as DemCoreg (Shean et al., 2016), Pybob’s `coreg_tools` or GeoUtils’s `dem_coregistration` that were libraries with no tests, limited documentation and relied on geospatial dependencies. xDEM was designed as a flexible toolbox, with many possible functionalities implemented. For example, the coregistration algorithms included the Nuth & Kaab (Nuth and Kääb, 2011) method, iterative closest point (Chen and Medioni, 1992; Besl and McKay, 1992) or correction of planar vertical biases or "deramping". However, some of these features were not mature or even experimental. Moreover, the toolbox model did not address the need of the CO3D mission for a standardized and rigorous DEM evaluation.

While xDEM focuses specifically on elevation data, it inherits its raster, vector and point cloud functionalities from GeoUtils[7], developed in parallel by GlacioHack. GeoUtils provides convenient and scalable geospatial methods for common tasks such as reprojection, raster-to-point interpolation, point gridding or vector masking. Both xDEM and GeoUtils depend on Rasterio, GeoPandas, and Pyproj for georeferenced calculations, and NumPy, SciPy (and optionally Numba or Dask) for its numerical efficiency and scalability.

2.3 Federation

In 2023, CNES and the GlacioHack collective established contact in order to explore potential synergies between demcompare and xDEM. This collaboration led to a 10-month study conducted by CS GROUP in 2024, which included a comprehensive audit covering legal, social, IT, and algorithmic aspects. The audit highlighted the strategic advantages of focusing on xDEM, including its more recent technological foundation, its larger user community, and its excellent documentation. These factors, combined with xDEM’s extensive feature set, made it the ideal candidate for unification.

Following the audit, CNES and the GlacioHack collective began federating their efforts under the unified tool xDEM. As a result, demcompare was no longer supported, and all future developments were integrated into xDEM. This transition ensures that the CO3D mission benefits from a robust, community-supported tool capable of handling large datasets and providing reproducible results. The integration of xDEM into the image calibration center environment further facilitates automated and rigorous DEM quality assessment, aligning with the mission’s goals of achieving high-precision global 3D products.

3. Recent contributions

Since the federation, many contributions have been made in xDEM. These include work primarily focused on qualifying 3D products, efforts related to scalability, and initiatives concerning organization.

[6] xDEM: `https://github.com/GlacioHack/xdem`
[7] GeoUtils: `https://github.com/GlacioHack/geoutils`

3.1 DEM evaluation

3.1.1 Blockwise coregistration To address spatially variable misalignments in large DEMs, xDEM implements a coregistration framework in which the domain is partitioned into smaller blocks. Coregistration is then performed independently within each block, enabling the estimation of spatially varying offsets not captured by global approaches. The resulting set of local transformations is subsequently interpolated to derive a continuous correction field. As for other parameters in xDEM, this continuous correction aims to be fully modular, supporting for instance any fit optimizer such as RANSAC (Fischler and Bolles, 1987) to allow robustness to a wide range of inputs.

Another benefit of blockwise coregistration is a straightforward chunk-by-chunk processing to limit memory usage and enable parallel execution on large datasets. However, scalability in xDEM is not limited to blockwise approaches: global coregistration methods are also being extended to support large datasets through out-of-memory reprojection, subsampling, and raster-to-point interpolation.

3.1.2 Workflows and command-line interface A series of pre-defined workflows coupled to a command-line interface are also being developed for xDEM. Workflows offer users predefined multi-step analyses with recommended methods and parameters. The command-line interface allows users less familiar with Python to run these workflows and analyze outputs in a straightforward way through a configuration file (see Listing 1). For instance, the `accuracy` workflow, which closely mirrors the functionality of demcompare, performs an accuracy assessment of an elevation dataset by comparing it to another reference dataset. This includes reading two DEMs, performing reprojection and change of vertical referencing when needed, estimating and correcting systematic alignment errors using any of xDEM’s coregistration, calculating final differences between the DEMs, and deriving statistics. This workflow is currently being extended to link to xDEM’s uncertainty quantification feature for estimating structured random errors, thereby providing a full accuracy assessment of the input elevation data. For ease-of-use, results are then compiled into a comprehensive report in both HTML and PDF formats (see Figure 2). Processing steps are described in Figure 1.

```
xdem [workflow_name] --config config_file.yaml
```

Listing 1. Workflow usage: a command-line call with a configuration file

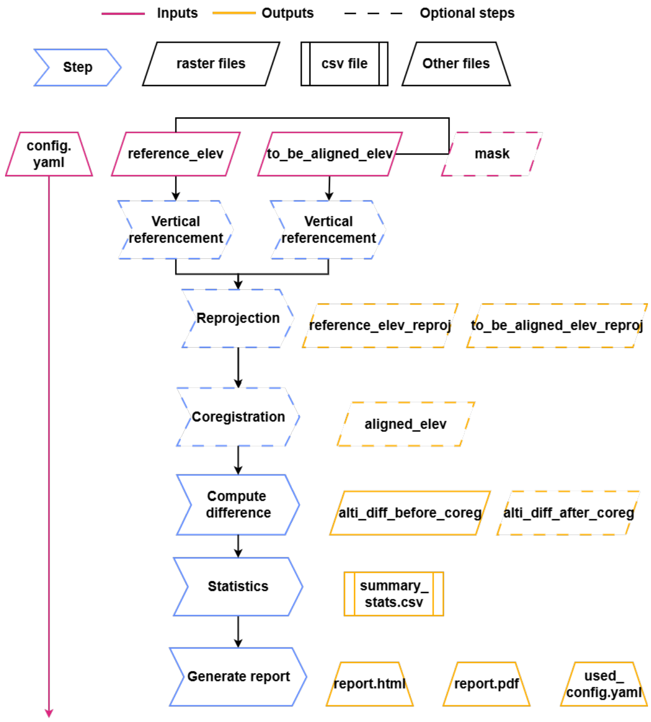


Figure 1. Accuracy workflow pipeline (source: https://xdem.readthedocs.io/)

Other workflows are in-development, such as the `topo` workflow to provide a topographical summary of a DEM. These workflows make data qualification more accessible and efficient for users of all skill levels. While they are currently experimental, we are refining their interfaces based on user feedback and planning performance improvements for future releases.

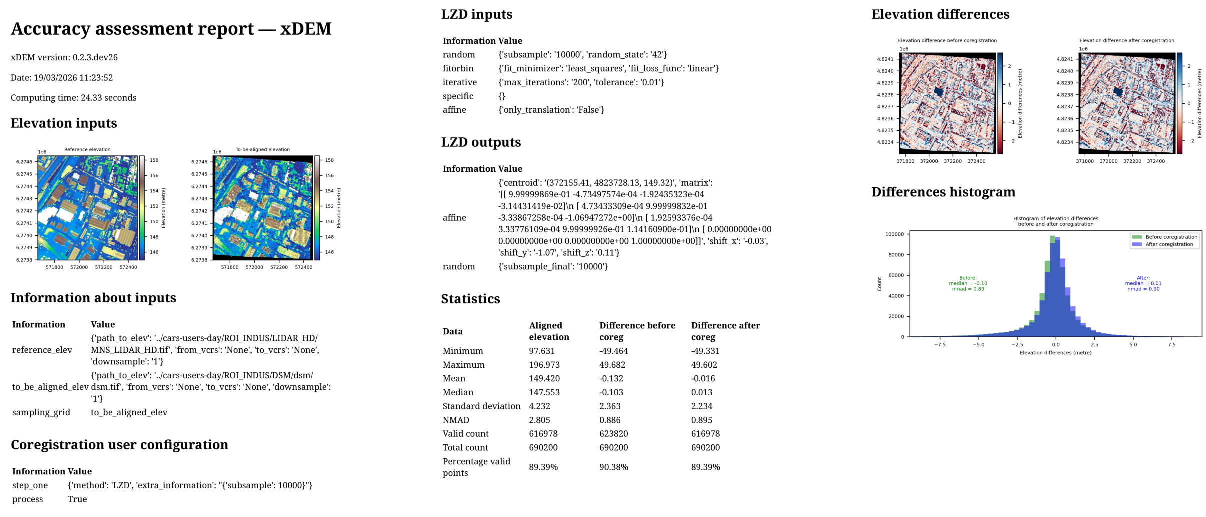
3.2 Scalability

Key improvements have enhanced the scalability of xDEM through the integration of Dask and Multiprocessing, together with the introduction of Xarray[8] and GeoPandas[9] accessors. Complex scalable routines for raster, vector or point cloud data were implemented in GeoUtils, such as out-of-memory reprojection or raster-to-point interpolation. Elevation-specific scalable routines, such as 3D affine transformation, reside directly in xDEM. Furthermore, with the addition of profiling tools and tests, we ensure that memory usage and computing time remain bounded to an expected level.

3.2.1 Dask / Multiprocessing with Xarray accessors Until recently, GeoUtils and xDEM relied entirely on their own data structures based on Numpy arrays and metadata attributes, such as a `geoutils.Vector` or `xdem.DEM`. Now, their functionalities are mirrored to work on Xarray and GeoPandas datastructures, better integrating with the Python geospatial ecosystem. This integration offers several key benefits. Indeed, scalability relies on three different mechanisms:

- **Deferred input/output** that refers to operations that modify only internal I/O metadata, avoiding reading the data entirely and postponing loading. GeoUtils and xDEM

[8] Xarray: `https://github.com/pydata/xarray`
[9] Geopandas: `https://github.com/geopandas/geopandas`



Accuracy assessment report — xDEM

xDEM version: 0.2.3.dev26

Date: 19/03/2026 11:23:52

Computing time: 24.33 seconds

Elevation inputs

Information about inputs

Information	Value
reference_elev	{'path_to_elev': '../cars-users-day/ROI_INDUS/LIDAR_HD/MNS_LIDAR_HD.tif', 'from_vcrs': 'None', 'to_vcrs': 'None', 'downsample': '1'}
to_be_aligned_elev	{'path_to_elev': '../cars-users-day/ROI_INDUS/DSM/dsm/dsm.tif', 'from_vcrs': 'None', 'to_vcrs': 'None', 'downsample': '1'}
sampling_grid	to_be_aligned_elev

Coregistration user configuration

Information	Value
step_one	{'method': 'LZD', 'extra_information': "{'subsample': 10000}"}
process	True

LZD inputs

Information	Value
random	{'subsample': '10000', 'random_state': '42'}
fitorbin	{'fit_minimizer': 'least_squares', 'fit_loss_func': 'linear'}
iterative	{'max_iterations': '200', 'tolerance': '0.01'}
specific	{}
affine	{'only_translation': 'False'}

LZD outputs

Information	Value
affine	{'centroid': '(372155.41, 4823728.13, 149.32)', 'matrix': '[[9.99999869e-01 -4.73497574e-04 -1.92435323e-04 -3.14431419e-02]\n [4.73433309e-04 9.99999832e-01 -3.33867258e-04 -1.06947272e+00]\n [1.92593376e-04 3.33776109e-04 9.99999926e-01 1.14160900e-01]\n [0.00000000e+00 0.00000000e+00 0.00000000e+00 1.00000000e+00]]', 'shift_x': '-0.03', 'shift_y': '-1.07', 'shift_z': '0.11'}
random	{'subsample_final': '10000'}

Statistics

Data	Aligned elevation	Difference before coreg	Difference after coreg
Minimum	97.631	-49.464	-49.331
Maximum	196.973	49.682	49.602
Mean	149.420	-0.132	-0.016
Median	147.553	-0.103	0.013
Standard deviation	4.232	2.363	2.234
NMAD	2.805	0.886	0.895
Valid count	616978	623820	616978
Total count	690200	690200	690200
Percentage valid points	89.39%	90.38%	89.39%

Elevation differences

Differences histogram

Figure 2. Accuracy assessment PDF report with LiDAR HD data as reference elevation and CARS Pléiades DSM as to-be-aligned elevation. LiDAR HD data were acquired between 28/05/2022 and 01/06/2022. CARS Pléiades DSM is calculated with CARS software (version 1.0) from Pléiades stereo-images acquired on 28/06/2022. A month separates the two datasets: CARS Pléiades DSM is the oldest data. It can be observed that a building has been constructed (blue on the image) and a building has been destroyed (red on the image).

support this through both their objects and accessors, allowing for instance to manipulate object metadata or select a subset without loading the underlying data, which implicitly loads only when necessary.

- **Chunked execution** that refers to processing raster data tile-by-tile instead of loading the full array into memory. It is implemented through two backends: Dask, used through Xarray accessors, and with Multiprocessing, used through the GeoUtils and xDEM objects. Figure 3 represents the reprojection with chunked execution, with a new CRS and a downsampling of 2.

- **Lazy execution** that refers to deferring computation until results are explicitly requested. This feature is only available through the Xarray accessors with Dask-backed arrays.

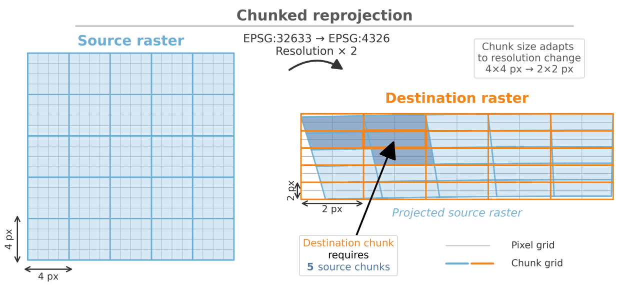


Figure 3. Chunked reprojection with a new CRS and a downsampling of 2 (source: https://geoutils.readthedocs.io/)

3.2.2 Profiling GeoUtils includes a built-in profiling tool that provides insights into function performance. This is not only useful for internal tests, but also for users to quickly grasp the performance of their routines. With profiling enabled and graph output activated, two HTML graph types are generated:

- **Icicle graph** showing time spent in each process step. Figure 4 represents the time spent in each decorated function `accuracy` workflow. This icicle graph shows the hierarchical structure of decorated functions and the time each function takes to execute. The largest rectangles represent the most time-consuming functions, with color coding indicating the duration, helping to identify performance bottlenecks.

- **Memory consumption graphs** for decorated functions. Figure 5 represents the memory consumption for each decorated function in the `accuracy` workflow.

Profiling helps identify resource-intensive methods, guiding optimization efforts.

3.3 Governance and development practices

In addition to the technical improvements, significant improvements have been made in the governance and development practices of xDEM.

3.3.1 License Firstly, the project has transitioned from the MIT license to the more software-adapted Apache v2.0 license to better align with the needs of the community and ensure broader compatibility. Indeed, xDEM dependencies are now compatible with Apache v2.0, unlike under the previous licence. Besides, the 3D software from CNES, such as CARS[10], which produces Digital Surface Model from stereo-images, and Bulldozer[11], which produces Digital Terrain Model from Digital Surface Model, are under this license.

3.3.2 Governance Now that CNES and GlacioHack are collaborating to maintain xDEM, a formal governance system has been established to ensure the smooth continuation of the

[10] CARS: `https://github.com/CNES/cars`
[11] Bulldozer: `https://github.com/CNES/bulldozer`

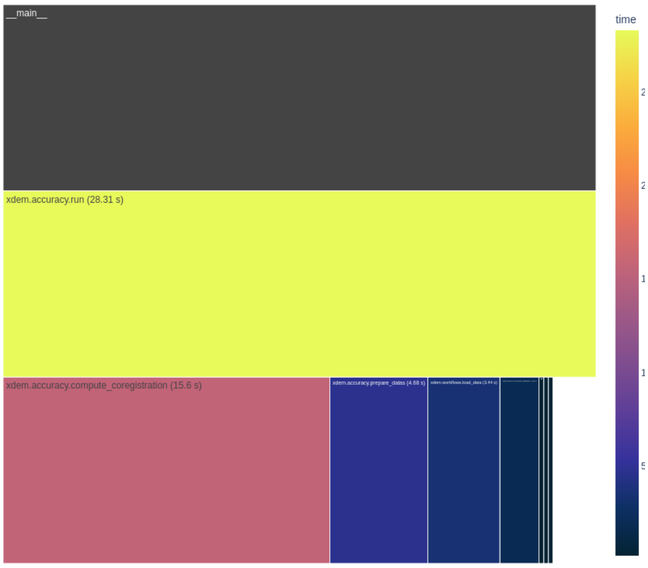


Figure 4. Time spent in each decorated function for the `accuracy` workflow from the example in Figure 2. The coregistration function is the most time-consuming one. The decorated functions are: load data, prepare data (reprojection), compute coregistration, compute statistics and compute histogram.

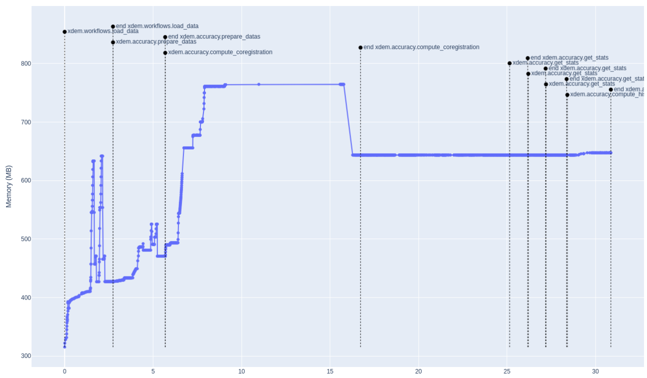


Figure 5. Memory consumption for each decorated function in the `accuracy` workflow from the example in Figure 2. The decorated functions are: load data, prepare data (reprojection), compute coregistration, compute statistics and compute histogram.

current collaboration and to encourage more contributors by providing a structured and inclusive development environment. To this end, three files were added:

- **Governance file**: This file outlines the rules and decision-making processes for the project, inspired by the MVG (Minimum Viable Governance) project[12].
- **Code of Conduct file**: This file sets the expectations for behavior within the project community, inspired by the Contributor Covenant [13].
- **Author file**: This file helps to highlight the community and ensures that authors retain ownership of their work.

3.3.3 Agile development Additionally, agile methodologies have been adopted to optimize the development process. A Product Owner (PO), responsible for the product vision, maintains and prioritizes the product backlog. For each sprint (four-week iteration), the development team selects and develops tasks from the sprint backlog. Regular ceremonies such as sprint planning and retrospectives ensure alignment and continuous improvement. Moreover, roadmap meetings are held to maintain a long-term vision and consistent progress toward project goals. These changes have enhanced transparency, sustainability, and collaboration efficiency among contributors.

3.4 Summary of xDEM functionalities

Finally, the contributions made over the last few years have enabled xDEM to offer a wide range of functionalities. All these features have evolved and are subject to further development, particularly as it is constantly being expanded over time. The main functionalities of xDEM are described in detail in the following section.

3.4.1 Coregistration xDEM includes varied coregistration methods and more precisely 3D affine transformations. These transformations correspond to 3D translations or rotations. All the methods implemented in xDEM are summarized in Table 1.

Table 1. Summary of supported 3D affine transformations

Affine method	Description	Reference
Nuth & Kaab	Translations	(Nuth and Kääb, 2011)
Least Z-difference	Translations and rotations	(Rosenholm and Torlegård, 1988)
Iterative closest point	Translations and rotations	(Chen and Medioni, 1992; Besl and McKay, 1992)
Coherent point drift	Translations and rotations	(Myronenko and Song, 2010)
Vertical shift	Vertical translations	N/A

[12] MVG: `https://github.com/github/mvg`
[13] `https://www.contributor-covenant.org/`

3.4.2 Vertical referencing xDEM also offers the possibility to manipulate vertical coordinate reference systems. Most DEM products do not yet come with a well-defined vertical reference, xDEM thus facilitates both their setting and conversion between reference systems.

3.4.3 Terrain attributes xDEM can derive a wide range of terrain attributes:

- **surface fit attributes** that rely on estimating local derivatives such as slope, aspect, hillshade and curvatures (profile curvature, tangential curvature, etc.);
- **windowed attributes** that rely on estimating local indexes often applicable to any window size such as topographic position index, terrain ruggedness index, roughness, rugosity and fractal roughness;
- and finally **frequency attributes** that rely on estimating relative frequency over the whole DEM such as texture shading.

3.4.4 Bias corrections xDEM implements 3D bias-correction methods that correspond to transformations that cannot be described as 3D affine methods in section 3.4.1. These methods are used to correct both systematic elevation errors and spatially structured random errors. All the methods implemented in xDEM are summarized in Table 2.

Table 2. Summary of supported 3D bias-correction methods

Bias-correction method	Description
Deramping	Correction with a 2D polynomial of degree N
Directional biases	Correct biases along a direction, often semi-periodic
Terrain biases	Correct biases along a terrain attribute (defined in section 3.4.3
Custom bias	Correct biases with any function

3.4.5 Uncertainty analysis Finally, xDEM includes uncertainty analysis tools that rely on concepts from the disciplines of spatial statistics and uncertainty quantification, tailored to DEM analysis (Hugonnet et al., 2022). While systematic errors of elevation data are corrected using 3D affine transformations (defined in section 3.4.1) and 3D bias-correction (defined in section 3.4.4), uncertainty analysis is used for quantifying and propagating random structured errors.

4. Conclusion and perspectives

The CO3D mission represents a significant advancement in the three-dimensional reconstruction of Earth’s continental surface, aiming to produce a global one-meter DSM in less than four years. The collaboration between CNES and the GlacioHack collective, notably the integration of the xDEM tool into the CO3D image calibration center, illustrates the benefits of shared efforts and open-source collaboration.

Several developments have been made on both sides to obtain a tool that can meet the requirements for the qualification of CO3D products. Blockwise coregistration is a major step forward in that direction, with ongoing developments to generalize its application to all coregistration methods. Other contributions have also helped improve ease-of-use and visualization, such as the implementation of different workflows and a command-line interface. These developments are still evolving based on user feedback. The implementation of a QGIS plugin is also underway and will help to expand the user community by offering a more accessible interface to those who are unfamiliar with the CLI or Python API. Additionally, the implementation of Xarray and Geopandas accessors further embeds xDEM within the Python geospatial ecosystem. These are key steps in cementing the tool’s scalability, enabling easy integration with Dask and Multiprocessing. In addition, profiling has been implemented to identify cost-intensive methods. Future developments will improve performance by optimizing these methods.

xDEM promotes transparency, accessibility, and community-driven innovation by embracing the principles of Free and Open Source Software (FOSS). Future developments could include fostering more collaborations of this kind, encouraging the development of open-source tools and establishing robust governance models to ensure a sustainable, inclusive growth. This approach benefits individual missions such as CO3D and contributes to the broader scientific community by promoting open collaboration and shared resources.

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