3D Product Quality Control in the CO3D Mission: A Critical Role

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Abstract

We present the qualification of 3D products as part of the CO3D mission. This mission aims at generating a global Digital Surface Model (DSM) of the Earth's landmass. Massive automatic production is a challenge in itself as the ground segment delivers more advanced data than those typically generated by optical missions. Unlike conventional workflows, where 3D products are often manually refined and validated, leading to substantial costs, the CO3D mission relies on a fully automated processing chain. Masks will also be included to describe the processing history and provide precise information on the altitudes restored. All of this data requires a comprehensive qualification approach with accurate reference datasets and dedicated evaluation methods in order to properly assess product quality. The paper describes all the tools, the qualification methods and reference data used, and provides an overview of the performance achieved by these new CO3D products.

1. Introduction

Successfully launched at the end of July, the two pairs of CO3D satellites (Lebègue et al., 2020) (French acronym for "Constellation Optique 3D") are now in orbit, ready to map all land areas as a Digital Surface Model (DSM) at 1 m Ground Sampling Distance (GSD). The CO3D mission is the result of a partnership between CNES, the French space agency, and Airbus, a private aerospace company, with the contribution of IGN, the National Institute of Geographic and Forest Information, for the definition and qualification of 3D products. Despite the strong experience of CNES and Airbus in optical Earth observation missions, notably with the SPOT and Pléiades satellite programs, CO3D introduces new challenges related to the large-scale production of 3D products. The purpose of this paper is to provide a detailed presentation of the CO3D mission, along with the evaluation methodologies, reference datasets that will be used during the qualification phase, and the expected performance levels of these new products.

2. CO3D Mission

The CO3D program is a challenging program, as it aims to generate a global DSM of the Earth in less than four years. To meet this objective, four small 300 kg satellites built by Airbus were launched from the French Guiana Space Center aboard a Vega-C launcher. They acquire images of the same area from multiple viewing angles, enabling 3D reconstruction through photogrammetric processing. In addition, satellites that operate in pairs in the same orbit have synchronized acquisition capabilities. It makes it possible to freeze moving objects as illustrated in Figure 1 and reconstruct them in 3D.

2.1 3D product as a Digital Surface Model

The 3D products will be generated by an operational processing chain called CODIP (Melet et al., 2020), which will integrate CARS software[1] for the 3D reconstruction.

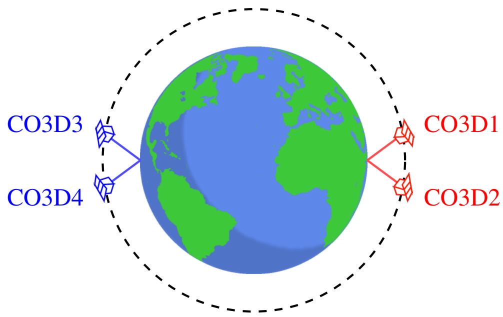

Figure 1. CO3D orbit configuration.

CARS and Pandora. CARS (Youssefi et al., 2020) is a multi-view stereo pipeline specifically designed to handle large volumes of satellite imagery. Other software solutions exist, such as MicMac (Rupnik et al., 2017) or Ames Stereo Pipeline (ASP) (Beyer et al., 2018), but the CO3D mission required a tool tailored to satellite data and large-scale production with a compatible license so that the pipeline could be delivered to Airbus. The 3D reconstruction process relies on photogrammetric principles; the observed shift between the two viewpoints (a left image and a right image) encodes the relative depth of the observed object (and thus the altitude in the context of satellite imagery).

Using images and associated geometric models as input, the processing chain first resamples the images into epipolar geometry. This transformation simplifies the matching problem by constraining pixel correspondences along a single direction. The Pandora software[2], integrated in CARS, then estimates pixel-wise disparities between the stereo pair. The displacement of a pixel from the left image to the right image can then easily be

[1] CARS: `https://doi.org/10.5281/zenodo.17406459`
[2] Pandora: `https://github.com/cnes/pandora`

converted into a position in both original images: simply consider the position of the current pixel in the left image, and for the right image, consider the position of the current pixel plus the calculated offset, then return to the original geometry via inverse projection to the epipolar geometry.

Once homologous points are identified in the images, the associated viewing sight lines are computed using the geometric model of the sensors. We then look for the 3D point that is closest to these two lines. Repeating this process for all pixels in the left image produces a dense 3D point cloud. For practical use, and given that a georeferenced raster representation is generally sufficient at the targeted resolution, this point cloud is projected onto a regular grid to generate the final DSM.

As part of the CO3D mission, two 3D product levels will be available by CODIP / CARS: the L3 level is dedicated to specific productions limited in size, typically smaller than 2,500 km², while the L4 level is the worldwide 3D product coverage, split in 0.25°x 0.25° tiles mesh. The products comply with the DGED Product Implementation Profile (Defence Geospatial Information Working Group (DGIWG), 2020)).

2.2 Geometric Refinement of Image Viewpoints

A major challenge in the mission is the correction of slight geometric misalignment between stereo image viewpoints to ensure the production of DSM with high vertical precision. The processing used during the In-Orbit Test (IOT) phase to make this correction before producing a DSM, is given below with a high-level description (see (Erblang et al., 2026) for more details).

The smallest DSM produced is created from two stereo images with a footprint of 5x7 km^2 on the ground. The attitude of the satellite is refined for both acquisitions following these two steps:

- Individual refinements which use the correlation of the image with Ground Control Points (GCP) from Space Reference Point (SRP) database (Chandelier and Coeurdevey, 2020) to improve its geolocation. Time dependent errors due to the mode of acquisition of satellites are also corrected at this stage.
- Stereo refinement where the spatio-triangulation of tied points (match found by the correlation of the two images) best matches elevation of Copernicus Digital Elevation Model (DEM).

One last step is performed when the site area exceeds 5x7 km^2 since several overlapping unitary scenes are acquired to cover the whole site and a global refinement of geometric models is required to minimize altimetric shifts between adjacent scenes.

2.3 Auxiliary products

In addition to the DSM, an endogenous orthoimage is calculated, and several masks that perfectly overlay the DSM are available:

- the Source Data Mask (SDM) is the origin of each pixel (photogrammetry, filling, water processing, etc.).
- the Performance Mask (PFM) provides relative altimetric accuracy for each point.
- the Time Stamp Mask (TSM) records the acquisition dates of the images used to compute the DSM.
- the Land Cover Mask (LCM) is a land cover map produced by the software SLURP (Smart Land-Use Reconstruction Pipeline) [3] (Tanguy et al., 2024) combined with Airbus cloud detection algorithms. For example, it is used to flatten the water surface.

Bulldozer. Photogrammetric reconstruction does not work everywhere: (e.g., occlusion, water areas), leading to data gaps. Therefore, to provide complete 3D models, interpolation methods are necessary. It is important to understand that these methods enable realistic rendering but not a reconstruction that corresponds to reality and has physical validity (hydro-compatibility). Thanks to SLURP, the CODIP chain is able to generate water masks that allow the filling of water-covered areas. While the sea is set to geoid height and lakes to a constant height, rivers have a height that varies along their course: we therefore aim to set it to a height that follows the edge of these watercourses. For occluded areas, where elevation cannot be directly observed, the values are estimated from a Digital Terrain Model (DTM). To generate DTM, CNES developed another open-source software called Bulldozer[4] (Lallement et al., 2023). The software uses the drap-cloth algorithm. The method simulates the progressive settling of a virtual cloth draped under the DSM surface. As the cloth comes into contact with the terrain, it adapts to the underlying topography while remaining constrained under elevated structures. The process iterates until the cloth reaches a stable equilibrium.

SLURP. Land-use masks are a third-party product in the 3D production chain. They play a key role in improving 3D rendering because the semantics of the landscape influences how it is rendered in 3D. The CO3D processing chain relies on SLURP software, an efficient tool designed to generate land-use / land-cover masks. It proposes several simple machine learning algorithms, each specialized for a given class. The different masks are then merged and regularized to produce the final LCM.

Water detection is a primary requirement to flatten the DSM to match the elevation of the shoreline of each water surface. The other classes could also improve the 3D reconstruction. For example, detecting building borders improves image matching by adapting correlation parameters to sharpen these discontinuities. Detection of low and high vegetation can outline areas where the DTMs should fit to the DSMs and support the extraction of DTMs from DSMs. Although these use-cases are not yet implemented in the operational 3D restitution pipeline, end users may use the LCM to build a custom DTM from CO3D DSM.

3. Qualification activities

An IOT period began after the launch. It is dedicated to image geometry calibration and the initial altimetric performance assessment against system requirements and is ongoing. It will be followed by a phase dedicated to the evaluation of 3D product performances.

[3] SLURP: `https://github.com/cnes/slurp`
[4] Bulldozer: `https://github.com/cnes/bulldozer`

3.1 System requirements

Altimetric performance requirements are given for a baseline-to-height ratio (B/H) of 0.3 and a one meter planimetric resolution DSM:

- The relative vertical performance over a 5×7 km^2 scene shall be less than 1 meter for slopes in the $[0 - 5]\%$ range and less than 1.5 meter for slopes in the $[5 - 20]\%$ range.
- The absolute vertical performance shall be less than 4 meters for slopes in the $[0 - 5]\%$ range and less than 5 meters for slopes in the $[5 - 20]\%$ range.
- The altimetric shift between two 5×7 km^2 adjacent scenes shall not exceed 0.6 meter.
- after refinement of ground processing using GCPs and all available images, the geolocation accuracy shall be less than 5 m with SRP.

3.2 Reference datasets

Our qualification activities require a large reference dataset, qualification techniques, and the support of IGN’s expertise in 3D qualification.

Reference datasets were prepared on several sites distributed in two areas: metropolitan France and a government area of interest. The qualification objectives differ slightly between these two contexts, resulting in minor variations in the reference data used.

- The sites located in metropolitan France are intended to allow for a precise evaluation of the absolute planimetric and altimetric accuracy of the CO3D DSM products, as well as the consistency of the associated masks (LCM, PFM). This evaluation relies on national reference datasets of recognized quality.
- The sites within the government area of interest are intended to validate the quality of DSM in a wide range of landscape types, including dense urban centers, tropical forests, sand dunes, cliffs, and high-relief mountainous areas.

Each site covers approximately 300 to 900 km² and was selected to represent a broad range of geomorphological and land-cover conditions. The following reference datasets are available for each site.

IGN High-density LiDAR DSM and landcover.[5] In metropolitan France, the national High-density LiDAR (Light Detection And Ranging) program provides the reference DSM. This program aims to deliver a 3D description of the territory with an accuracy never achieved before at a country scale. The system combines a laser scanner, GNSS positioning, and an inertial measurement unit to generate a georeferenced point cloud. Points are first classified into several classes and then used to produce:

- the LiDAR HD DSM, computed from first-return echoes,
- the LiDAR HD DTM, computed from last-return echoes and post-processing.

The resulting products reach an accuracy greater than 50 cm RMSE in planimetry and 10 cm RMSE in altimetry. Since the LiDAR HD point cloud is classified, a land cover mask is derived and adapted to ensure consistency with the CO3D LCM classes.

Pléiades-Neo high quality DSM. For all sites, and particularly where LiDAR HD is not available, reference DSM are computed from Airbus Pléiades Neo (PNeo) imagery (30 cm resolution satellites) acquired under high-quality stereoscopic configurations, consisting of at least two stereopairs or even better three triplets. The images are registered using the SRP database to ensure geometric consistency with CO3D products (the same ground control point database as the CO3D Mission). Then dense image matching is performed using MicMac. One DSM is computed for each stereo pair acquired along the same orbit (four for two stereo pairs and nine for a three-triplet configuration). The individual DSM are merged to produce a 1 m resolution reference DSM. This approach offers two main advantages:

- high planimetric accuracy ensured by SRP data base,
- minimization of occlusions and noise through multi-view.

Accuracy assessment: The accuracy of PNeo DSM was evaluated over metropolitan France sites where LiDAR HD DSM are available. First, geometric registration was assessed using precise ground points (pedestrian crossings, road intersections). These points were stereo-restituted, on the one hand, from SRP-registered PNeo stereo-pairs and, on the other hand, from national databases (BD Ortho®[6] and RGE Alti®[7]). The observed planimetric bias is less than 50 cm and the altimetric bias is less than 1.5 m. Then the PNeo DSMs were compared to LiDAR HD DSMs. The observed vertical shift is less than one meter. A planimetric shift of approximately two meters was detected, likely attributable to the accuracy of the SRP over France. This shift is eliminated using the xDEM’s coregistration function. xDEM is defined in section **??**. The remaining outliers are mainly explained by temporal differences between datasets (building construction or demolition, vegetation seasonality).

ICESat-2 filtered points. The ICESat-2 laser altimetry data is used to strengthen the assessment of the altimetric performance of CO3D. The ATL08 product, freely available from the National Snow and Ice Data Center (NSIDC), was selected. ATL08 provides along-track terrain and canopy heights derived from photon-counting measurements of the ATLAS sensor, along with several quality and descriptive parameters. Given the very large number of ICESat-2 observations, filtering is necessary to eliminate unreliable measurements prior to comparison.

Filtering strategy: A Multi-Layer Perceptron neural network was trained to classify ICESat-2 points as valid or invalid with respect to the target vertical accuracy. The training data set consists of nearly 500,000 points distributed in five landscape categories: urban, rural/forest, mountainous, desert, and coastal. The data set was divided into 1/3 for training and 2/3 for testing. Each ICESat-2 point was labeled by comparing its elevation to the LiDAR HD DSM:

[5] LiDAR HD: `https://geoservices.ign.fr/lidarhd`

[6] BD Ortho®: `https://www.data.gouv.fr/datasets/bd-ortho-r`

[7] RGE Alti®: `https://www.data.gouv.fr/datasets/rge-alti-r`

https://doi.org/10.5194/isprs-archives-XLIX-B1-2026-547-2026

- 0: The deviation from the reference exceeds the target altimetric threshold,
- 1: The deviation is within the target accuracy threshold.

The trained model predicts:

- a binary classification (reliable or unreliable point),
- a confidence score (between 0 and 1)

The tests show a strong correlation between the predicted confidence score and the actual proportion of valid points within the test data set. Filtering was performed using a 1 m vertical accuracy threshold.

Stereo restitutions. For both metropolitan France and government area of interest, manual stereo-restitutions are performed by experienced operators using PNeo stereo imagery. Among available multi-view configurations, a stereo pair minimizing shadows and occlusions is selected to ensure optimal photo-interpretation conditions. The main features captured are as follows:

- Buildings with several points for each one (e.g. roof ridges, eaves, building bases),
- Roads avoiding narrow streets and vegetation interference
- Terrain breaklines (e.g. ridges and talwegs)
- Quoted points (e.g. summits)

Unlike raster-based DSM comparisons, which provides global assessment of the quality and focuses on global effects (vibrations, bias, etc.), manual stereo restitution focuses on the geometric fidelity of terrain and object representation (building shapes, street restitution, slope discontinuities).

Land use / Land cover

Validating land-use/land-cover maps is particularly challenging due to incomplete ground truth data, potential spatial discrepancies, and differences in classification nomenclatures. Finally, land cover can sometimes vary seasonally (e.g.,vegetation cover, lakes that dry up in summer) or even temporally within day periods, especially in coastal areas affected by tidal variations.

The adopted approach first involved developing the SLURP software and validating the water and vegetation masks with sparse manual annotations. These masks were generated from PHR (Pleiades High Resolution) images, with a ground resolution (0.7m) close to CO3D GSD. A variety of test datasets were then used to generate and validate the masks across a wide range of landscapes (urban, rural, coastal areas) and various seasons.

Among the available reference datasets, LiDAR HD in the France areas was used as ground truth. During IOT, CO3D acquired several images over Montpellier, which we were able to overlay with PHR images and then compare the performance of the masks with the LiDAR HD reference. Several limitations of LiDAR HD as a reference quickly emerged: for each geographic coordinate, LiDAR HD can identify multiple land cover classes (for example, road and high vegetation, if a tree covers the road). Another limitation is that some classes are highly dependent on the acquisition date (particularly in agricultural areas). Despite these limitations, in this area (see Figure 2), we can observe that the largest area of water and vegetation is consistent between the SLURP mask and the LiDAR HD reference.

Figure 2. Extract of CO3D Montpellier image with the LiDAR HD Ground Truth (left) and the SLURP mask (right) below.

3.3 Qualification tools

To support qualification activities, CNES and IGN have developed a set of complementary tools.

xDEM. During the specification phase of the CO3D mission, there was a need for a software tool that could validate 3D products, particularly by easily computing absolute and relative vertical accuracy. At the time, no existing state-of-the-art software met these requirements.

To address this gap, CNES proposed developing a generic open-source tool that could be reused for future missions. Initially, CNES created its own tool, demcompare. However, as the open-source community evolved, CNES collaborated with the GlacioHack collective and joined the governance of their open-source software, xDEM[8] (Hugonnet et al., 2022). Although xDEM was not originally designed for quality assessment, its potential was recognized, leading to discontinuation of demcompare. All future developments were then integrated into xDEM.

xDEM provided key functionalities for 3D coregistration and uncertainty estimation, which are essential for robust performance assessment. To meet the CO3D qualification activities' requirements, new features were implemented to xDEM, focusing on scalability, visualization capabilities, and accessibility. Notable enhancements included the development of blockwise coregistration and predefined workflows.

Ultimately, xDEM was integrated into the image calibration center environment, enabling a rigorous and automated evaluation of the 3D data produced by the CO3D mission.

IGN Tools. IGN has developed a dedicated internal tool to compute statistical indicators assessing the consistency between CO3D products and vector reference datasets, such as ICESat-2 and stereo products. The tool provides object-based statistics (mean, minimum, maximum, L90, LE95, RMS, etc.) and aggregates them into comprehensive performance summaries. It also proposes a visualization of dicrepancies directly in standard GIS environments, which facilitates interpretation and analysis.

[8] xDEM: `https://doi.org/10.5281/zenodo.48096977`

Altimetric performance assessment metrics. To assess vertical performance of CO3D DSM using a reference, both are first co-registered using the Nuth and Kääb method (Nuth and Kääb, 2011) implemented in xDEM. Then the altitude differences are computed and classified by class of slope mentioned in the system requirements. Finally, the performance metrics are derived as follows:

- $QAD90 = \text{percentile}_{90}(|\Delta h - h_{bias}|)$ is the relative altimetry performance, where $QAD90$ is the 90th Quantile Absolute Deviation (QAD) around the median, Δh is the altitude differences between the CO3D DSM and the reference, and h_{bias} is a positive constant bias calculated as the median of Δh.
- $QAD90 + h_{bias}$ is the absolute performance.

4. First qualification results

The results presented here are based on stereo acquisitions of the Chad qualification site by CO3D1/CO3D2 satellites with a $B/H = 0.2$ (see Figure 3). A total of 4×3 unitary scenes were collected (an example is shown in Figure 4) and processed using the geometric processing chain and performance assessment tools described in sections 2.2 and 3.3.

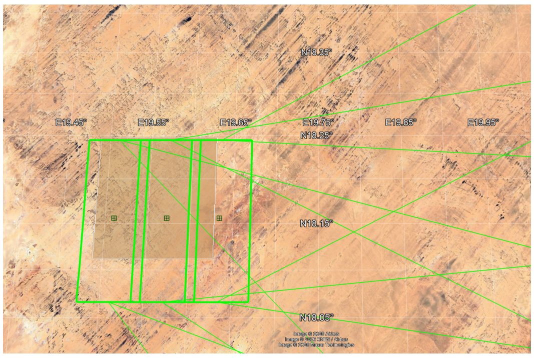

Figure 3. Acquisition (in green) of Chad site with a North-South CAP tasked on CO3D1/CO3D2 satellites and PNEO footprint (transparent area).

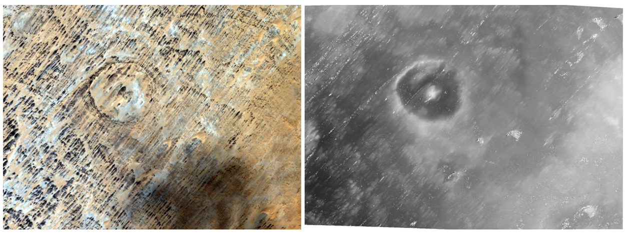

Figure 4. Left: Unitary scene received from Chad acquisition. Site is mainly composed of rocks surrounded by sand with 40 meters variation relief with at least 60% of pixels in $[0-5]\%$ slope class. Right: corresponding 1 meter resolution DSM.

Figure 5 shows the comparison between the DSM merged and the PNEO reference, leading to the following observations:

- no significant along-track altimetric ramp is observed (this can come from an error in the satellite attitude model). However, a approximately 80 cm ramp is visible across-track. This effect has been attributed to discrepancies between Copernicus and PNEO, suggesting that the geometric model fitting over-relies on Copernicus data and not enough on SRP.
- altimetric shifts are visible at the boundaries of overlapping unitary DSMs.

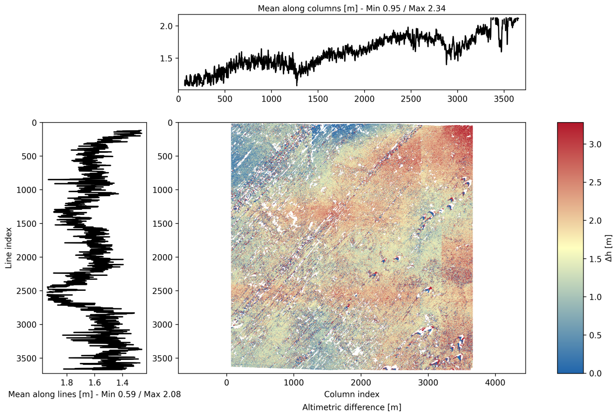

Figure 5. Altitude difference map between CO3D and PNEO DSMs with mean profile Along-Track on the left and Across-Track on top. 4 meters resolution has been used since it decreases processing time and we are only interested to low resolution geometric defects here.

The altimetric performances obtained are shown in Figure 6:

- relative vertical accuracy is higher than requirements for both slope classes,
- absolute vertical accuracy meets the requirements, except for two scenes.

These results are expected to be better with a higher B/H ratio (e.g. $B/H = 0.3$) as altimetric accuracy is expected to depend on B/H. Ongoing work on Geometric Refinement of Image Viewpoints processing, including update on focal plane cartography, is also expected to improve altimetric performance.

Cross validation of Absolute Altimetric Performance Using ICESat-2. The Chad site is covered by more than 44,000 filtered ICESat-2 points. The terrain is relatively flat and lacks vegetation, providing favorable conditions for evaluating absolute altimetric performance. Table 1 summarizes the statistical comparison between the CO3D DSM elevations and the ICESat-2 reference points for all points, as well as for subsets with slopes below 5% and 20%.

Overall, the results demonstrate low bias and vertical dispersion consistent with mission expectations. The spatial distribution of elevation differences (Figure 7) confirms the good agreement between the CO3D DSM and ICESat-2 data, with no large-scale systematic errors.

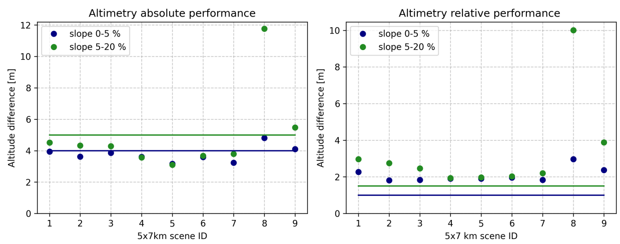

Figure 6. Absolute and relative altimetry performance result on Chad checked at CO3D unitary scene scale.

It indicates that the 1.5 m bias observed in absolute performance presented in the previous section comes mainly from PNEO and is consistent with the accuracy of PNEO announced in 3.2. By subtracting it from the result, the absolute performance of CO3D meets the requirements. As Copernicus altimetry is calibrated on ICESat-2 and PNEO is only calibrated on SRP altimetry for the Chad site, it can explain the bias observed.

Table 1. Assessment of absolute altimetric performance using ICESat-2

Class	Points	Mean	Sigma	RMSE	LE90
All	44356	0.072	1.297	1.299	1.862
Slopes < 5%	38137	0.065	1.192	1.194	1.757
Slopes 5–20%	1365	0.136	1.569	1.574	2.023

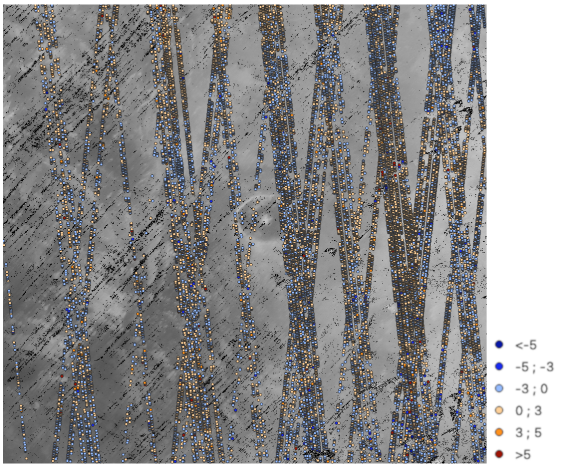

Figure 7. Spatial distribution of ΔZ between ICESat-2 points and the CO3D DSM.

5. Conclusion and perspectives

This paper presented the main components of the CO3D 3D processing chain: software involved in the CO3D image processing chain, qualification tools, reference datasets, along with a first altimetric performance assessment of the CO3D DSM.

These first results demonstrate that the CO3D mission is capable of producing high-quality 3D products that meet the performance requirements (even under non optimal acquisition configurations ($B/H = 0.3$)).

Further work will focus on:

- extending the assessment to many other qualification sites covering various landscapes (ongoing work on France sites, Marrakech, etc.),
- testing the impact of B/H ratio on altimetric precision,
- evaluating the effect of synchronized acquisitions to reduce motion artifacts,
- improving model refinement strategies for large scale sites,
- developing evaluation of LCM and PFM masks.

In general, the CO3D mission opens new perspectives for fully automated large-scale 3D mapping, combining high spatial resolution, global coverage, and advanced processing capabilities. The methodologies and tools developed for this program are expected to benefit future Earth observation missions.

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