ANALYSIS OF GEDI’S ELEVATION ACCURACY FROM THE FIRST AND SECOND DATA
PRODUCT RELEASES OVER INLAND WATERBODIES

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ABSTRACT

In this study, water level estimates from the Global Ecosystem Dynamics Investigation Lidar (GEDI) were validated against in situ gauge station records over Lake Geneva. The performances of the first and second releases (respectively V1 and V2) of the GEDI data products were compared. The influence of the following parameters were analyzed: (1) the signal-over-noise ratio (SNR), (2) the width of water surface peak within the waveform (gwidth), (3) the amplitude of the water surface peak within the waveform (A), (4) the viewing angle of GEDI (VA), and (5) the acquiring beam. The comparison between V1 and V2 elevations showed that V2, overall, provided elevations with a more constant bias and fewer deviations to in situ data than V1. In addition, by choosing GEDI shots with VA ≤ 3.5°, the unbiased RMSE (ubRMSE) of GEDI elevations was 27.1 cm with V2 (r=0.66) and 42.8 cm with V1 (r=0.34). Results also show that the accuracy of GEDI (ubRMSE) does not seem to depend on the beam number and GEDI acquisition dates for the most accurate GEDI acquisitions (VA ≤ 3.5°). Regarding the bias, a higher value was observed with V2 but with lower variability (54 cm) in comparison to V1 (35 cm). Finally, the bias showed a slight dependence on beam GEDI number.

Index Terms— LiDAR; GEDI; Lakes; Product V001; Product V002

1. INTRODUCTION

In this study, we are interested in evaluating the accuracy of the recently launched spaceborne-based full-waveform LiDAR sensor, the Global Ecosystem Dynamics Investigation (GEDI) on board the International Space Station (ISS). GEDI, which became operational in 2019, is equipped with three 1064 nm lasers with a pulse repetition frequency (PRF) of 242 Hz. One of the lasers’ power is split in two, and are hereafter referred to as coverage lasers, while the remaining two operate at full power, hereafter referred to as power lasers. These four lasers are equipped with beam dithering units (BDUs) that rapidly deflect the light by 1.5 mrad in order to produce eight tracks of data. The acquired footprints along the eight tracks are separated by 600 m across track, and 60 m along the track, with a footprint diameter of 25 m.

Since the launch of GEDI, there have been few studies that assessed its accuracy for the estimation of in-land water levels [1,2,3]. The first study conducted by Fayad et al. [1], used the first two months of GEDI acquisitions (mid-April to mid-June 2019) to assess the accuracy of GEDI altimetry over eight lakes in Switzerland. For these two months, they reported a mean difference between GEDI and in situ water elevations (bias) ranging from -13.8 cm (under estimation) to +9.8 cm (over estimation) with a standard deviation (SD) of the bias ranging from 14.5 to 31.6 cm. The study conducted by Xiang et al. [3] over the five great lakes of North America (Superior, Michigan, Huron, Erie and Ontario) using five months of GEDI acquisitions (April to August 2019) found a bias ranging from -32 cm (under estimation) to 11 cm (over estimation) with a SD that ranged from 15 to 34 cm. Finally in the study of Frappart et al. [2] which assessed the accuracy of GEDI data over ten Swiss lakes using acquisitions spread over seven months (April to October 2019) found a bias that ranged from -15 cm (under estimation) to +21 cm (over estimation) with a SD ranging from 10 cm to 30 cm.

There are several factors affecting the physical shape of the waveform and therefore the accuracy of LiDAR’s altimetric capabilities (viewing angle at acquisition time, water specular reflection, clouds and their composition). These potential sources of uncertainty on GEDI acquisitions have not been studied in depth in previous studies due to mostly the quantity of available GEDI acquisitions, which at most, only covered acquired shots spread over seven months of acquisitions. Moreover, the Land Processes Distributed Active Archive Center (LP DAAC) recently released version two (hereafter referred to as V2) of the preprocessed GEDI data. V2 should provide better geolocation (latitude, longitude, elevation) accuracy in comparison to the first release (hereafter referred to as V1) (mean horizontal geolocation error of respectively 11.9 and 25.3 m for 95% of the data for V2 and V1). Nonetheless, improved elevation accuracies are unknown.

The objective of this study is the assessment of the vertical accuracy of GEDI shots from the second release of GEDI data in comparison to the first release.

2. STUDY AREA AND DATASETS

2.1. Study area
This study was conducted over Lake Geneva (France-Switzerland), the largest lake by surface area and volume in Central Europe. Overall, the lake has a surface area of 580 km², with a maximum length of 72 km, and 15 km in width. The lake mean depth is 80 m, and reaches a maximum depth of 310 m.

2.2 GEDI data

Two GEDI data products were used in this study, the level 1B (L1B), and level 2A (L2A). The L1B data product contains detailed information about the transmitted and received waveforms, the location and elevation of each waveform footprint, and other ancillary information, such as mean and standard deviation of the noise, and acquisition time. The L2A data product contains data of elevation and height metrics of the vertical structures within the waveform. For both the L1A and L2B, we downloaded both release versions V1 (L1B: [4], L2A: [5]) and V2 (L1B: [6], L2A: [7]) from the LC DAAC. The dataset comprises 44 acquisition dates over Lake Geneva, spanning from April 2019 until September 2020 (available GEDI datasets in both V1 and V2). For each acquisition date, GEDI acquires data over eight parallel tracks.

For both versions (V1 and V2) of the L1B dataset, we first extracted the geolocation of the ground peak from the waveforms (latitude, longitude, and elevation). The latitude, longitude, and elevation correspond to the latitude, longitude and elevation of the lowest detected mode in the L2A dataset (i.e. surface return). Next, the viewing angle (VA) and the signal to noise ratio (SNR) were calculated for each waveform. The viewing angle was calculated for each shot (s) using the following formula:

\[
VA_s = \tan^{-1} \frac{d_{sl}}{a_i} \quad (1)
\]

Where \(d_{sl}\) is the haversine distance between the location of an acquired GEDI shot (s) and the location of the GEDI instrument (i) projected at nadir onto the WGS84 reference ellipsoid and \(a_i\) is the altitude of GEDI instrument over the referenced ellipsoid at acquisition time of shot (s). The location of the GEDI instrument for each acquired waveform was extracted from the latitude_instrument and longitude_instrument variables in the L1B dataset, while its altitude was extracted from the altitude_instrument variable. VA is expressed in degrees (°).

The SNR was calculated based on the formulation of Nie et al. [8], and is defined as:

\[
SNR = 10 \log_{10} \left( \frac{A_{\text{max}} - \mu_n}{\sigma_n} \right) \quad (2)
\]

Where \(A_{\text{max}}\) is the maximum amplitude within an acquired waveform, \(\mu_n\) is the mean background noise and \(\sigma_n\) is the standard deviation of the background noise. \(A_{\text{max}}\) is defined as the maximum of up to 20 possible values of rx_modeamps available in the L2A dataset. rx_modeamps corresponds to the amplitude of each detected mode within the waveform. \(\mu_n\), and \(\sigma_n\) are defined in the L1B data product by the variables mean and stddev, respectively. SNR is expressed in dB.

Within the period between April 2019, and September 2020, GEDI acquired 92,414 shots spread on 44 dates over Lake Geneva. Nonetheless, not all the shots are usable since LiDAR signals can be affected by atmospheric conditions that attenuate the LiDAR signal. Therefore, to remove non-viable shots, several filters were applied:

(1) Since a footprint acquired over a water surface should only have a single return or mode, as such, all acquired GEDI shots with a number of detected modes different from one (num_detectedmodes ≠ 1, from L2A data product) were removed.

(2) After the application of the first filter, a second filter was applied that removed the shots having an elevation difference to the SRTM DEM of more than 100 m.

For this study, after the application of the previously mentioned filters, 51,807 shots were retained and used, or around 56% of all the acquired shots.

Finally, given that gauge station levels are provided with respect to the Swiss height measurement system (LN02), and the water levels derived from GEDI are geolocated with respect to the WGS84 ellipsoid, conversion of the GEDI reported elevations with respect to Swiss height measurement system (LN02) was necessary. This conversion was made using the REFRAME geodesic web service provided by the Swiss federal office of topography (swisstopo, https://www.swisstopo.admin.ch/en/maps-online/calculation-services/reframe.html accessed on 20 September 2021).

2.3 In situ water levels

Water level records from the in situ gauge station over lake Geneva were obtained from the Hydrology Department of the Federal Office for the Environment (FOEN) (www.hydrodaten.admin.ch).

3. RESULTS

Using the 51,807 selected shots, we observe that elevations acquired in the first released version (V1) had a bias (resp. ubRMSE) to in-situ elevations of 32.9 cm (resp. 66.2 cm). In contrast, for the second release (V2) the bias increased to 71.1 cm (resp. 68.9 cm). And while the ubRMSE is relatively similar (66.2 cm vs. 68.9 cm) for both releases (V1 and V2), the ubRMSE from V1 is higher than what was previously obtained in Fayad et al. [1] (ubRMSE between ~14 and ~31 cm) and Frappart et al. [2] (ubRMSE between ~10 and ~30 cm) using smaller subsets of V1 over lake Geneva. Therefore, an in depth analysis of these differences as a function of different acquisitions parameters (amplitude (A) and width (gwidth)) of the surface return mode, SNR, and Viewing angle) is required.

In addition, Figure 1 shows that the difference between GEDI V1 and in situ elevations is not well correlated to GEDI
V2 and in situ elevations. It can be seen that some of the GEDI elevation data are quite close when comparing the V1 and V2 versions while for some of GEDI elevations are generally higher with V2 than with V1 (the dots on the upper part of Figure 1). Moreover, approximately 21% of the shots have an absolute difference of more than 0.5 m ($|\text{GEDI } V1 - \text{ in situ} - (\text{GEDI } V2 - \text{ in situ})| > 0.5$ m), and around 7% of data have a difference of more than 2 m.

Figure 1. Difference between GEDI V2 and in situ elevations as a function of the difference between GEDI V1 and in situ elevations. Each dot in the figure corresponds to a GEDI shot.

The analysis of the precision of GEDI acquisitions by date showed that for three acquisition dates (February 20, July 07, and July 17 2020), a high bias (mean elevation difference between GEDI and in situ elevations) was observed. For the remaining dates, the bias varied between -1 and +1 m (Figure 2). The analysis of ubRMSE showed values lower than 0.5 m except for seven dates in 2020 where high ubRMSE values were observed (February 20, July 07, July 19, July 22, July 25, and August 18, 2020). Moreover, for most of these dates, the ubRMSE form V1 is higher than that of V2 (Figure 2).

Figure 2. Mean difference between GEDI and in situ elevations of V1 and V2 product releases according to GEDI acquisition dates (bias, a) and the unbiased root mean squared error of GEDI elevations (ubRMSE, b).

The accuracy of GEDI elevations has been analyzed according to waveform SNR for four SNR ranges: SNR $< 10$ dB; 10 dB $\leq$ SNR $< 15$ dB; 15 $\leq$ SNR $< 20$; and SNR $\geq 20$. Figure 3 shows that the deviation of the reported elevations by GEDI decreased with increased SNR. Indeed, lower differences were obtained in general with waveforms with a SNR higher than 15 dB (63.4%) in comparison to waveforms with lower SNR. These results were observed for both the first (V1) and second release (V2) of the GEDI data products. Moreover, the results reported in Table 1 show that the ubRMSE for SNR $> 15$ dB was 28.4 cm for V2 in comparison to 43.2 cm for V1.

For the shots with SNR less than 15 dB, V2 does not show increased precision in comparison to V1, and both releases show imprecise elevations with an ubRMSE close to 100 cm.

Finally, in terms of bias, the V2 release shows a bias that decreases from 133.8 cm for SNR $< 10$ dB to 86.3 cm for SNR between 10 and 15 dB, and reaches a minimum of 56.8 cm for SNR higher than 15 dB. In contrast with the first release (V1), the correlation between the bias and SNR is less evident, and varied between 19.8 and 46.3 cm depending on the range of the analyzed SNR (Table 1).

Figure 3. Difference between GEDI and in situ elevations as a function of waveform SNR. Each point within the figure corresponds to a GEDI shot.

| SNR (dB) | V1 GEDI – in situ elevations (cm) | V2 GEDI – in situ elevations (cm) | GEDI shots count |
|---------|---------------------------------|---------------------------------|-----------------|
| SNR $\leq 10$ | 26.2 | 94.2 | 133.8 | 32.8 | 3,944 |
| 10 < SNR $\leq 15$ | 19.8 | 91.7 | 86.3 | 90.9 | 15,047 |
| 15 < SNR $\leq 20$ | 34.7 | 47.3 | 54.0 | 31.1 | 18,774 |
| SNR $> 20$ | 46.3 | 36.1 | 60.5 | 24.0 | 14,041 |

Table 1. Statistics of the difference between GEDI and in situ elevations according to the four classes of waveform’s signal to noise ratio (SNR).

The effect of the VA on the accuracy of the GEDI elevations has been conducted over four VA ranges: VA $< 1.5^\circ$; 1.5$^\circ$ $\leq$ VA $< 3.5^\circ$; 3.5$^\circ$ $\leq$ VA $4.5^\circ$; and VA $\geq 4.5^\circ$ (between 4.5$^\circ$ and 6.5$^\circ$).

The results presented in Figure 4 show that the ubRMSE of GEDI elevations increased with increasing VA, and this was observed for both GEDI data product releases V1 and V2. The results also showed that the correlation between ubRMSE and VA are significantly lower for V2 in comparison to V1. For VA less than 1.5$^\circ$, the ubRMSE was similar for both V1 and V2 (26.6 cm for V1 and 23.4 cm for
For the shots acquired with a VA between 1.5° and 3.5°, the ubRMSE with V2 was smaller than V1 with an ubRMSE of 23.9 cm for V2 and 44.8 cm for V1. Finally, for both V1 and V2, the ubRMSE increased to around 1 m with viewing angles greater than 3.5°. 74.6% of filtered GEDI data were acquired with a VA less than 3.5° and had an ubRMSE of 42.8 cm for V1 and 27.1 cm for V2.

Concerning the mean elevation difference (bias) between GEDI and in situ elevations, we observe an increase of the bias for V2 when VA increases. It increases from 33.9 cm for VA < 1.5° to 162.4 cm for VA between 4.5° and 6° (Table 2). For the V1 product, the bias seems to depend less than V2 on the viewing angle range (fluctuates between 12.7 cm and 43.5 cm).

![Figure 4](image_url)  
**Figure 4:** Unbiased root mean squared error of GEDI elevations (ubRMSE) as a function of GEDI’s viewing angle (VA). Each point corresponds to an acquisition date.

| VA (°) | bias  | ubRMSE | bias  | ubRMSE | GEDI shots count |
|-------|-------|--------|-------|--------|------------------|
| VA < 1.5° | 12.7  | 26.6   | 31.9  | 23.4   | 11,997           |
| 1.5° ≤ VA < 3° | 43.5  | 44.8   | 62.7  | 23.9   | 27,534           |
| 3° ≤ VA < 4.5° | 39.4  | 113.1  | 64.4  | 96.5   | 5,626            |
| VA ≥ 4.5° | 19.1  | 104.5  | 162.4 | 110.0  | 7,550            |

**Table 2:** Statistics of the difference between GEDI and in situ elevations according to the four classes of GEDI’s viewing angle (VA).

4. CONCLUSIONS

In this study, GEDI’s ability to measure and monitor water levels was assessed against in situ water levels across Lake Geneva. Both GEDI’s data-product release versions V1 and V2 were used. The assessment was performed as a function of the signal-over-noise ratio (SNR) and the viewing angle of GEDI (VA). The analysis results showed that the best criterion to filter less accurate GEDI waveforms is based on the viewing angle (VA). Indeed, for acquisitions with VA higher than 3.5°, the ubRMSE was 2.5 times higher than acquisition with VA less than 3.5°. Finally, the comparison between V1 and V2 elevations showed that V2 provides a better accuracy of water levels. Indeed, by choosing GEDI shots with VA ≤ 3.5°, the ubRMSE was 27.1 cm with V2 and 42.8 cm with V1. Nonetheless, V2 elevations had higher bias than V1, with a bias of respectively 54 and 35 cm.

5. ACKNOWLEDGMENT

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