ICESAT FULL WAVEFORM ALTIMETRY COMPARED TO AIRBORNE LASER ALTIMETRY OVER THE NETHERLANDS

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ABSTRACT:

Since 2003 the spaceborne laser altimetry system on board of NASA's Ice, Cloud and land Elevation Satellite (ICESat) has acquired a large world-wide database of full waveform data organized in 15 products. In this research three products are evaluated over The Netherlands. For this purpose the raw full waveform product, the derived Gaussian decomposition product and the global land evaluation product are compared to laser data from the Dutch national airborne laser altimetry archive AHN. Using the CORINE land cover 2000 database allows us to compare ICESat to AHN elevation profiles with respect to the land cover classes forest, urban, bare land/low vegetation and water. This comparison shows that a large average height difference of 5.7 m occurs over forest, while much smaller differences of 1.24 m over urban areas, of 0.43 m over bare land/low vegetation and of 0.07 m over water are found. The reason for this large difference over forests is that the standard processing of NASA does not take the position of the last Gaussian mode of the waveform into account. Incorporating results from a full waveform processing procedure allows us to determine improved ICESat profiles. Comparing the improved profiles shows that the average difference with the AHN profiles over forest is reduced to -0.38 m, while the average differences for the other land cover classes do not exceed -0.75 m. Encountered limitations are discussed in the conclusions.

1 INTRODUCTION

The Ice, Cloud and land Elevation Satellite (ICESat) was launched in January 2003 to observe the cryosphere, the atmosphere and also to measure land topography profiles and canopy heights (Zwally, 2002). These objectives are accomplished using the Geoscience Laser Altimeter System (GLAS) in combination with precise orbit determination (POD) and altitude determination (PAD). Since 2003 ICESat has acquired a huge database of raw and processed data, organized in the 15 data products GLA01, . . . , GLA15 (Brenner et al., 2003). The GLA01 level 1A product contains the raw full waveform data. The GLA05 level 2 altimetry product contains the centroid location of the full waveform as a result of NASA's waveform fitting method. The GLA14 product is also a level 2 product, consisting of global elevation data for non polar land regions.

The ICESat GLA14 elevation data are obtained by combining the GLA01 ICESat full waveform data with the precise position data as obtained by the POD/PAD system. The full waveform data are sampled as relative intensities in 200 bins for sea and 544 or 1000 bins for land, depending on which of the three lasers is used. A time stamp pair of each transmitted pulse and consecutively returned pulse (the full waveform) is recorded by the GLAS system and is used to calculate a travel time or range. This range is then used to compute the elevation of the area illuminated by the laser pulse. Moreover, the time stamp of the returned waveform can be measured at some typical bin positions of the waveform like the beginning, the centroid and the end. Consequently, the elevation will vary according to the variations in the range. The GLA14 elevation product is obtained on the basis of the range as derived from the centroid of the waveform. This elevation is therefore also called the mean elevation (Harding and Carabajal, 2005).

The accurate digital elevation model of the Netherlands (AHN) was acquired between 1996 and 2003 and is based on airborne laser altimetry, with a point density of at least 1 point per 4m×4m area in leaf-off conditions. There are four levels of detail: raw point cloud, and interpolated grid data of 5m×5m, 25m×25m and 100m×100m (Heerd et al., 2000). The raw point cloud is separated into vegetation points and ground surface points. It has to be noted that the filtering of the entire point cloud concentrated especially on vegetation, building points may therefore remain in the set of ground surface points. All data is in ASCII format files with XYZ coordinates given in the RDNAP coordinate system (Rijksdriehoeksmeting and Normaal Amsterdams Peil) (RDNAP, 2007).

In this paper, we first compare elevation profiles derived from ICESat GLA14 data to profiles derived from AHN ground surface data. Second, we will propose and evaluate a method to determine the bare earth elevation on the basis of a combination of GLA14 data, waveform centroid data of GLA05 data and processed full waveform GLA01 data. As most improvement is expected for waveforms over complex terrain, comparison results are differentiated with respect to land cover type. Four classes are distinguished: forest, urban, bare land and water. Waveforms are divided into these land cover classes according to the CORINE Land Cover 2000 database (CLC2000, 2006). It will be shown how to use the obtained profiles to find individual waveforms showing particular behaviour. This is illustrated in detail in three examples of waveforms over forest.

2 STUDY AREA AND DATASET

2.1 Study area

The area of study is the Netherlands, bounded approximately by 3^0E to 7^0E longitude and 50^0N to 54^0N latitude which contains a large variety of land cover types. Figure 1 shows a map of the digital elevation model (AHN) of the Netherlands, colored by height.

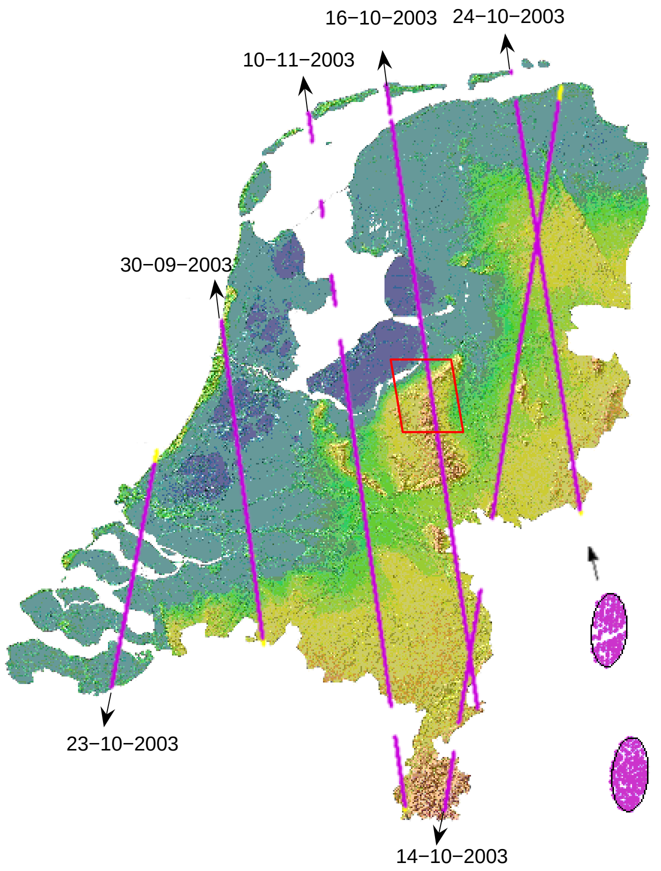

Figure 1. Study area: ICESat ground tracks (magenta) displayed with the actual height model of the Netherlands (AHN). The upward arrows indicate ascending tracks and the downward arrows descending tracks. In the bottom right corner two ICESat footprints filled with AHN points are shown.

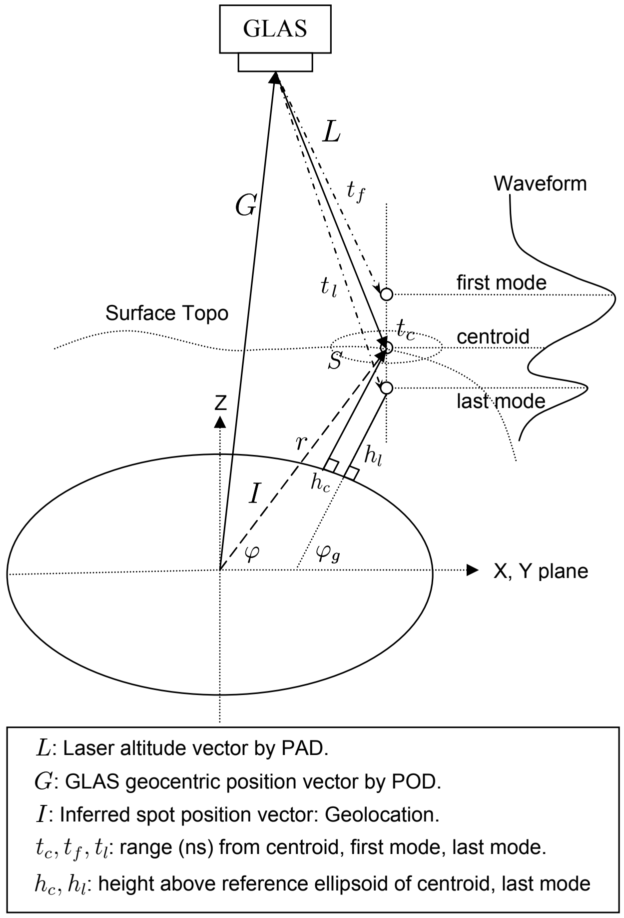

Figure 2. Principal of ICESat geolocation and surface elevation determination.

2.2 CORINE Land Cover 2000 database (CLC2000)

The CORINE Land Cover 2000 database (CLC2000) was initiated by the European Environment Agency (EEA) and the Joint Research Centre (JRC). The CLC2000 database originated from the year 2000 but was actually obtained during a 3-year period from 1999 to 2001, with a horizontal geolocation accuracy of 25m based on satellite images of Landsat 7 ETM+ with 25m pixel resolution. The CLC2000 data product was obtained from the Landsat data via a computer-assisted visual interpretation of the satellite images, under the requirements of a scale of 1:100 000, a minimum mapping unit of 25 hectares and a pixel resolution of 100m (Perdigão and Annovi, 2006). The CLC2000 classification was hierarchical and distinguishes 44 classes at the third level, 15 classes at the second level and 5 classes at the first level. Detailed information of land cover levels can be found at the metadata section of the CLC2000 on the European Environment Agency website (CLC2000, 2006). The total thematic accuracy of the CLC2000 database was almost 95%. The database was geo-referenced in the European reference system (Hazeu, 2003).

2.3 ICESAT/GLAS

GLAS uses a laser altimeter to measure the distance between the satellite and the earth surface. The instrument time stamps each laser pulse emission, and measures the echo pulse waveform from the surface. GLAS acquires elevation profiles of the entire earth along tracks that are revisited in a 183-day repeat cycle, with 70m diameter footprints spaced every 175m. A waveform, recording laser back-scatter energy as a function of time, is digitized in 544 consecutive bins at a temporal resolution of 1ns over land for each footprint (NSIDC, 2005). The land waveform of 15cm vertical resolution yields an 81.6m height range (544 waveform bins×15cm/bin) for laser L1 and 150m (1000 bins×15cm/bin) for laser L3 (Harding and Carabajal, 2005). GLAS carries three different laser altimeters, L1, L2 and L3. Laser 1 was turned off shortly after the Spring 2003 campaign, to be replaced by Laser 2. Laser 2 operates in both height ranges.

2.3.1 ICESat data overview: Among 15 GLAS data products, we investigate the products of GLA01, GLA05 and GLA14. The data sets we consider were acquired in the period from 2003-09-25 to 2003-11-18 and are all from release 26. There are six tracks with 6594 waveforms in total (Figure 1). The footprints of these waveforms are elliptical, its power distribution has a central maximum, while energy decreases towards the boundary. The size of the ellipse is 95m×52m on average (Harding and Carabajal, 2005).

The GLA01 is a raw level 1 product that contains the full waveform data. The GLA14 is a level 2 product of land surface elevation. Due to the potential complexities of land returns including possibly combined influences of slope, roughness, vegetation and cultural features, this level 2 land product was obtained by using a land-specific range[1]. The land-specific range is defined as the travel time from the GLAS sensor to the centroid of the received waveform signal (see Figure 2) and stored in the GLA05. This

[1] land-specific range means not in polar or ocean regions

land-specific range is then used for the computation of geolocated latitude, longitude and footprint elevation after all instrumental, atmospherical and tidal corrections have been applied (Brenner et al., 2003).

2.3.2 Principal of determination of geolocation and surface elevation:

A geolocated surface elevation, S, is determined as a sum of a laser altimeter vector, L, and a ICESat/GLAS geocentric vector, G, with respect to the center of mass of the earth (see Figure 2). The laser altimeter vector includes the GLAS laser pointing angle and a range, t_i, between the GLAS instrument and the surface as identified by measuring a travel time of a transmitted pulse until its return as a waveform. The range is then calculated as a half-travel time multiplied with the speed of light. The geocentric vector represents the orbit position of the ICESat satellite with respect to the center of mass of the earth. Therefore the laser spot or geolocation is inferred by the sum of these two vectors. The surface elevation is obtained by converting the geocentric laser spot position (r, φ, λ) to ellipsoidal height and geodetic latitude and longitude (h, φ_g, λ).

In Figure 2, the land-specific range from GLAS to the ground surface can be calculated based on different waveform parameters like the waveform centroid or the height of the first or last mode of the waveform. Using the first mode gives a shorter range and results in a higher elevation point. The first mode results from elevation points of trees, forest or artificial features like buildings. Using the centroid of the waveform gives an average elevation while the last mode potentially represents the ground surface.

3 METHODOLOGY

A flowchart of the methodology is shown in Figure 3. For comparison between ICESat and AHN, both data sets need to be available in the same georeferenced coordinate system, for which RD-NAP is chosen. The GLA14 data are first converted into RDNAP coordinates. Next those AHN ground data are extracted whose horizontal position is within the given GLA14 footprint ellipses. Because the ICESat footprint has an approximate diameter of 70 meter, the AHN points within the footprint need to be interpolated to a representative elevation point. For ICESat two profiles are determined, one based on the GLA14 'mean' surface elevations only, the other derived from combining the GLA14 elevations with the results of the processing of the GLA01 waveforms and the centroid of GLA05. Both profiles are compared to the same profile of the corresponding interpolated AHN elevations, leading to the two results to be compared and discussed.

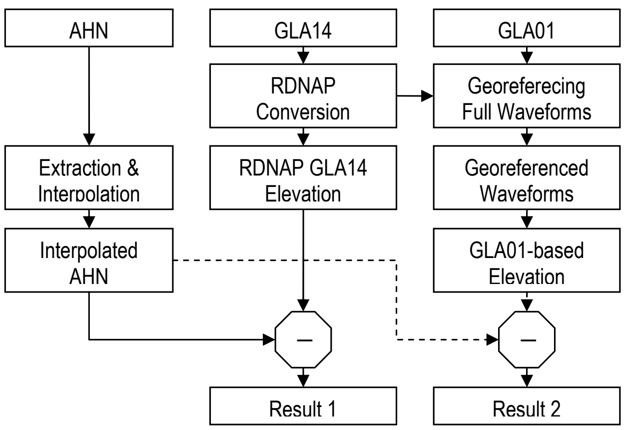

Figure 3. A methodology flowchart.

3.1 Interpolation of AHN data

A 70m-diameter ICESat footprint contains approximately 700 AHN data points. Therefore it is necessary to compute a mean AHN elevation for the purpose of comparing elevation profiles of AHN and ICESat data. To avoid effects of clusters in the spatial distribution of the AHN points, the AHN points are first interpolated to a regular grid, prior to the calculation of a mean AHN height. Based on the average point density of the AHN data of 0.20 point/m^2, a grid cell size of 4m×4m is chosen. Figure 4 shows a typical distribution of raw AHN points together with the regular grid points.

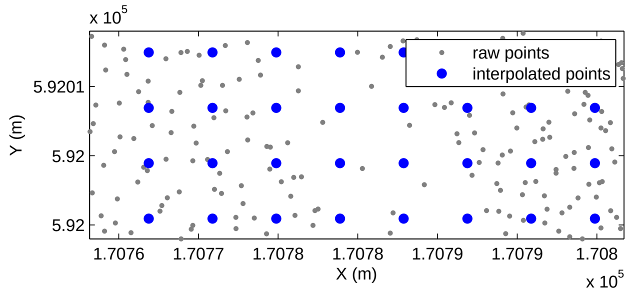

Figure 4. Raw AHN ground points (gray) and interpolated grid points (blue).

3.2 Height difference between GLA14 and interpolated AHN

A mean AHN elevation is obtained from interpolating the regular grid points within an ICESat footprint ellipse. This mean elevation is then subtracted from the ICESat GLA14 elevation of that footprint to obtain an AHN-GLA14 height difference. In this study, six ICESat tracks or six elevation profiles are used. Compare Table 1 and Figure 1 for an overview of the ICESat tracks. The differences over the total of the six tracks are averaged to obtain the final results as shown in Table 2.

3.3 Derivation of GLA01-based elevation data

The georeferenced waveform is decomposed into a maximum of six Gaussian components which allows to derive waveform parameters as amplitude, width and location of each Gaussian

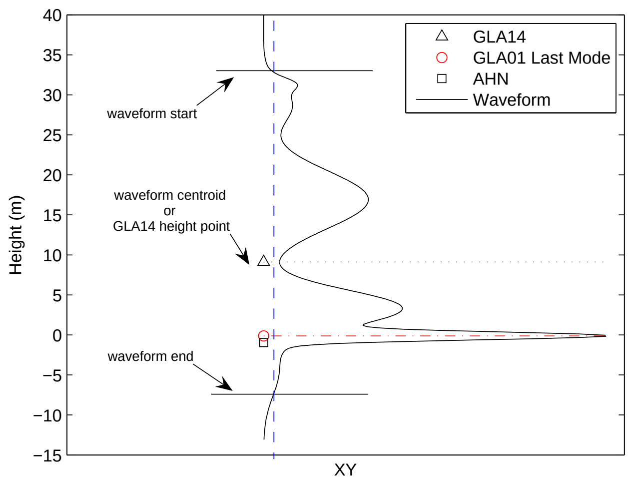

Figure 5. A waveform (black curve) is georeferenced by matching the waveform centroid (horizontal dotted line) to a GLA14 elevation point (black triangle). The GLA01-derived elevation is the centroid of the last peak (red circle).

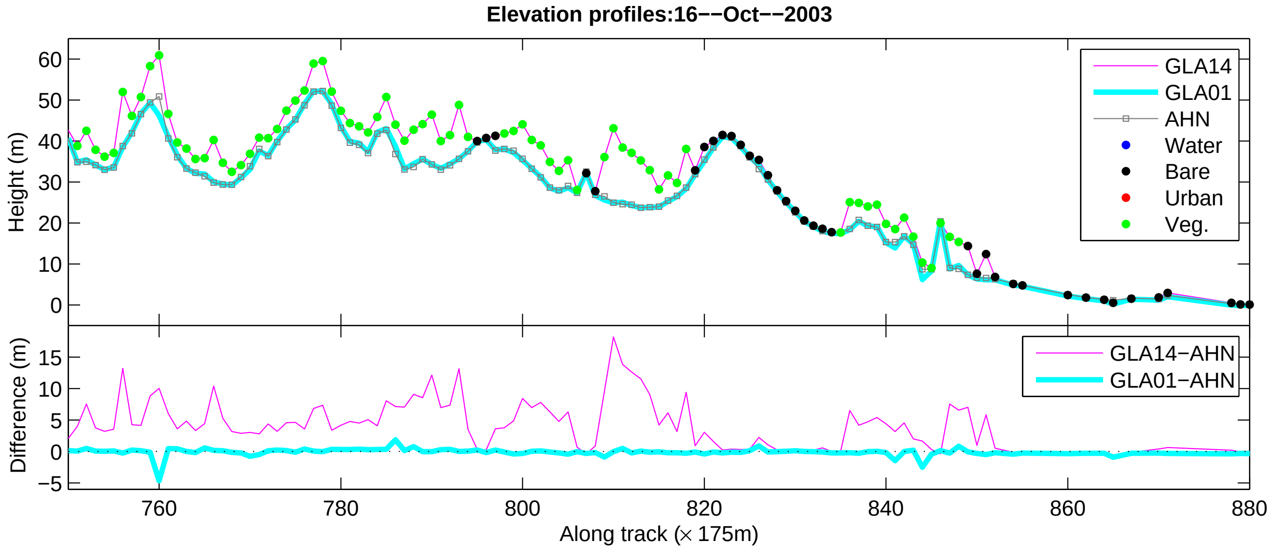

Figure 6. Top: Elevation profiles based on ICESat GLA14 data (red line), AHN data (black squared line) and ICESat GLA01 data (cyan line). Bottom: height differences between AHN and GLA14 (red) and AHN and GLA01 (blue). This profile corresponds to the red box in Figure 1.

mode (Duong et al., 2006). The first Gaussian refers to the highest point in the illuminated footprint which typically corresponds to a tree top or building roof. The centroid of the complete waveform corresponds to the average height of the objects in the footprint, while the last Gaussian mode is resulting from the lowest elevation in the footprint. Over flat terrain the lowest elevation mostly corresponds to the elevation of the ground surface. As Dutch topography is in general flat, the last Gaussian or last mode will be used in this research to obtain a ground surface elevation.

In Figure 5, the ICESat GLA14 elevation is represented by a black triangle; the black square represents the mean AHN elevation within the 70m-diameter footprint. For georeferencing the waveform (black curve), the waveform centroid (horizontal dotted line, black) is matched with the GLA14 elevation point. Therefore, the last mode is the most suitable representation of the ground elevation in the ICESat data (red circle). Finally the 'last mode elevation' of the ground surface is extracted by subtracting the distance between the centroid and the peak of the last mode from the GLA14 elevation.

4 RESULTS AND COMPARISON

4.1 Waveforms used

The waveforms from six ICESat tracks are assigned to different land cover classes based on the CLC2000 land cover database. On average, 97% of the ICESat measurements to the ground were successful, whereas in the remaining 3% percent, no data was acquired. One possible reason is the weather (e.g. cloud cover, data acquisition was in September-November). A number of 6594 waveforms is used, 595 waveforms are over vegetation, 790 over urban areas, 3472 over bare land and 149 over water (Table 1). About 20% of the waveforms was removed from analysis due to one of the following reasons:

- Some noisy waveforms could not be decomposed by the Gaussian fitting algorithm.
- No AHN points are available within the waveform footprint.
- Many ICESat pulses of the 24-10 track along 100km, see Figure 1, coincide with a cloud layer (our assumption) of at least 200m height and are therefore not considered reliable.

	Number of ICESat waveforms						
Track	Date	F	U	B	W	Total	Lost
1	30-09	72	158	456	28	795	81
2	14-10	89	316	933	16	1534	180
3	16-10	305	88	777	36	1515	309
4	23-10	8	54	351	42	584	129
5	24-10	2	17	361	0	979	599
6	10-11	119	157	594	27	1187	290
Total		595	790	3472	149	6594	1588

Table 1. Number of ICESat waveforms used: F (Forest), U (Urban), B (Bare land) and W (Water). The column 'Lost' gives the number of waveforms that were discarded because of e.g. high noise level, large height differences (200m) between the GLA14 and the AHN elevation or missing AHN data.

4.2 Height differences AHN–GLA14 vs AHN–GLA01

	GLA14 – AHN terrain, (m)			
Tr.	F	U	B	W
1	4.68±4.5	2.01±3.2	0.26±1.4	−0.66±1.2
2	6.62±2.9	1.81±2.5	0.79±2.1	0.59±1.4
3	6.76±3.5	1.44±3.5	0.57±1.7	−0.13±0.9
4	7.47±5.7	0.85±1.5	0.48±1.1	0.21±0.7
5	4.52±1.0	1.12±1.3	0.35±1.2	N/A
6	3.89±3.1	0.19±2.0	0.14±1.8	−0.35±1.4
Total	5.66±3.5	1.24±2.3	0.43±1.5	−0.07±1.1

Table 2. Height differences and its standard deviation between GLA14 and AHN

In Tables 2 and 3 the average height differences between the AHN elevation profiles and the GLA14 'mean elevation' (Tables 2) and the GLA01 'ground elevation' (Tables 3) are given. As expected, it shows that the average height difference between the 'mean elevation' and the AHN profiles is maximal over forested areas (5.66m). The differences are smaller over urban (1.24m) and bare land (0.43m) and minimal over water (0.07m). This is further illustrated in Figure 6. where a profile of 22.5km is shown along

	GLA01-derived – AHN terrain, (m)			
Tr.	F	U	B	W
1	−0.75±1.2	−0.84±3.0	−0.86±1.4	−1.81±1.8
2	−0.29±1.4	−1.11±2.3	−0.48±0.9	−0.49±0.7
3	−0.25±1.5	−1.73±2.0	−0.53±1.0	−1.54±1.4
4	−0.33±0.7	−0.58±0.8	−0.33±0.8	−0.22±1.0
5	−0.18±0.1	−0.45±0.8	−0.29±0.5	N/A
6	−0.49±1.8	−1.42±2.5	−0.58±1.1	−1.25±1.2
To.	−0.38±1.1	−1.02±1.9	−0.51±0.9	−1.06±1.2

Table 3. Height differences and its standard deviation between GLA01-derived elevation data and AHN

the ICESat track of October 16, 2003. Clearly, large differences of up to 20 m occur in forested areas. The difference between the waveform centroid, giving the GLA14 'mean elevation' and the surface elevation as given by the AHN points is larger in case of a wide spread multi-modal waveform. These multi-modal waveforms occur in urban and certainly in forested areas. The width of the waveforms is further increased in case the terrain is not flat.

Table 3 shows the differences between the ICESat last mode or 'ground elevation' profile and the AHN profile. The average height difference over forest is significantly reduced from more than five meter to less than half a meter, while the spread in height difference is reduced by about 70% as well. For the other three land cover classes no significant improvement is found. The improvement over forest is visualized in Figure 6. The bottom image shows that the ICESat 'ground elevation' profile (in cyan) is always closer to the AHN profile than the ICESat 'mean elevation' profile. It is also visible that the ICESat 'ground elevation' profile is sometimes even lower than the AHN profile. This can be explained as follows. If the terrain is curved, interpolation of the AHN laser points within the ICESat footprint will result in a mean AHN elevation value higher than the lower terrain points. Meanwhile the height of the peak of the last mode can be positioned below the mean AHN elevation, resulting in a negative offset. Moreover, building points still remain in the set of the AHN ground points therefore it also results a height difference in a negative value.

4.3 Waveform examples

The profile in Figure 6 allows to look for specific examples that give insight in the differences between the three heights that are considered, the ICESat 'mean elevation', the ICESat 'ground elevation' and the AHN mean of the ground points. Below three typical examples are discussed. The first example is an 'out of the book' forest example, in the second case the canopy thickness is so large that the visible ICESat ground return is ignored by the decomposition algorithm while in the third example the ICESat ground return is totally absent due to the high canopy thickness.

4.3.1 Regular canopy thickness example: Figure 7(a) shows a case were taking the ICESat 'ground elevation' gives clearly a better value than the ICESat 'mean elevation', when compared to the mean AHN ground elevation. The AHN vegetation points (green) and ground points (black) precisely match to the ICESat raw full waveform (red) and to the fitted waveform (dashed black). The peak of the last Gaussian mode at 10m height corresponds to the average height of the AHN ground points within the ICESat 70m footprint. The peak of the second-last Gaussian mode corresponds to the average height of the low vegetation at 10m–15m that is also represented by the AHN points. The first Gaussian peak represents the average height of the canopy. The width of the first Gaussian gives a measure for the canopy depth. This example illustrates, that spaceborne full waveform altimetry can be a possible method for extraction of vegetation height

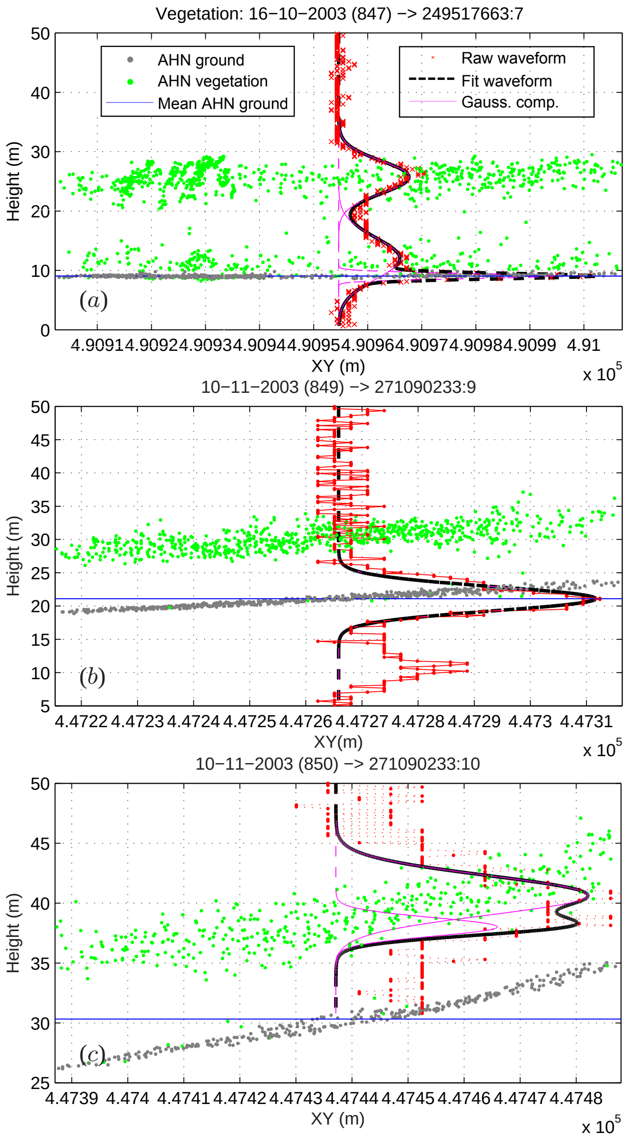

Figure 7. Three waveforms over forest. Good agreement between AHN and GLA14 is obtained for the top panel but insufficient results were found for the middle and bottom panel.

and vegetation characterization on single shot basis. The return energy, which is also recorded by GLAS, is about 20 fJ. This is well above the threshold of 5fJ (Fricker et al., 2005), under which the measurement noise increases. These high noise levels can be caused by atmospheric forward scattering and degradation of the laser transmitted power over time. Both effects lead to a decrease in received energy (and therefore SNR).

4.3.2 Higher canopy thickness: (i.) Figure 7(b) shows a raw waveform (red) with two dominant peaks. It agrees with the AHN data in the sense that it has one peak corresponding to the AHN ground points and one larger peak corresponding to the dense vegetation points. The last peak is ignored however by our waveform decomposition step due to the high noise level in the waveform. However, the distance between the lower and the higher peak of the raw waveform corresponds very well to the vegetation height whereas the absolute height may not be correct. Comparing Figure 7(b) and Figure 7(a) shows that the noise level is about three times higher in the lower example. In this case, the return waveform energy of 1.58 fJ which is very low compared to the threshold of 5 fJ (Fricker et al., 2005).

4.3.3 High canopy thickness: Figure 7(c) shows a case where the ICESat waveform shows only one mode, and where we need the AHN data to tell us that in fact this one mode corresponds to an unpenetratable forest canopy. In this case the ICESat 'mean elevation' and the ICESat 'ground elevation' are equal, but both higher than the AHN ground point elevation. This shot is a direct neighbor (175m) of the shot shown in Figure 7(b). The return energy is 3.40 fJ. This value is also below the 5fJ threshold.

4.3.4 'Glowing' effects: In Figure 8, a series of waveforms with systematic underestimation of the (surface) height is shown. Although the Gaussian components of the waveforms could be reconstructed, all but the first mode are weakly determined. Apparently these erroneous modes demonstrate some kind of 'glowing' effect. This assumption is supported by considering the orthophoto of the footprint locations: in most cases the footprints cover flat terrain which should result in one waveform mode only. Possible error sources for this behaviour are foreward scattering by cloud cover or problems with the signal detection at the GLAS receiver unit for very low energy returns. In this case, the return energy ranges between 0.29 fJ to 2.72 fJ. Such waveforms could be automatically removed by increasing the requirements in the waveform decomposition step or by imposing a threshold on the minimal return energy.

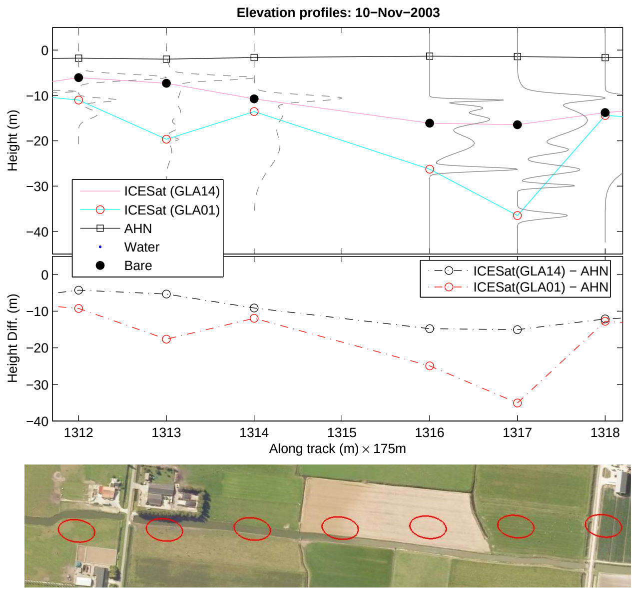

Figure 8. Elevation profiles (top) and height differences (middle) of ICESat, GLA14 and GLA01-derived elevations for some bad cases. At the bottom the ICESat footprints overlaid on a Google Earth image are shown.

5 CONCLUSIONS

In this paper we have compared three laser altimetry profiles. One based on ground return points from airborne laser data of the Dutch national height product AHN, and two based on ICESat data. NASA provides height data in the GLA14 product that are based on the centroid of the returned ICESat waveform. By considering the position of the last mode in ICESat's raw return waveforms a more realistic ground surface profile can be obtained from the ICESat data that is on average -0.38m below the mean AHN height, with an average standard deviation of ±1.1m.

Study of the three profiles gave us examples where the high forest canopy block almost all ICESat laser energy. This gives one explanation for the remaining differences between ICESat ground elevation' profiles and the AHN ground surface profiles. Neglecting the terrain slope may be another error source that should be corrected for in future. Further research should focus on two directions: those footprints were the ICESat waveform shape match the shape of a waveform built up out of AHN points can be used to assess the accuracy of ICESat georeferencing. On the other hand, analysis of the height difference in the three profiles will lead us to further examples were current waveform processing still fails and should be improved.

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