Error Analysis of ICESat Waveform Processing by Investigating Overlapping Pairs over Europe

Hieu Duong and Roderik Lindenbergh
Delft University of Technology
Delft Institute of Earth Observation
and Space systems
Delft, the Netherlands
Email: {v.h.duong, r.c.lindenbergh}@tudelft.nl

Norbert Pfeifer
Vienna University of Technology
Institute of Photogrammetry and
Remote Sensing,
Vienna, Austria
Email: np@ipf.tuwien.ac.at

George Vosselman
International Institute for
Geo-Information Science
and Earth Observation - ITC
Enschede, the Netherlands
Email: vosselman@itc.nl

***Abstract*—Full waveform laser altimetry is a recently developed method to obtain a complete vertical profile of the height of objects in the footprint as illuminated by a laser pulse. The richness of the signal also complicates the processing. One way to improve the processing strategy is to analyze differences of waveforms that should be very similar because they were obtained at approximately the same time and location. Such waveform pairs are still difficult to find. Here it is shown how to use the archive of ICESat space-borne altimetry data over Europe to determine a set of tenths of thousands of at least partial overlapping waveform pairs. The differences in the values of the waveform parameters, median energy, waveform extent, relative returned energy and intensity distribution are determined and discussed. As a case study, three typical pairs of almost perfectly overlapping waveforms are shown, were considerable differences are still occurring. In all three cases an explanation for these differences is found and discussed. Further analysis of the waveform pairs in this database is expected to considerably improve automatic processing of full waveform data.**

I. Introduction

In January 2003, NASA launched a new Lidar acquisition mission. Since then, the Ice, Cloud and land Elevation Satellite system (ICESat) is orbiting at an altitude of 600km, fulfilling objectives like measuring polar ice elevation changes or determining height of vegetation canopies along topographic profiles. These objectives are accomplished using the on-board Geoscience Laser Altimeter System (GLAS) combined with precise orbit determination. GLAS uses one laser altimeter at a time to transmit a laser pulse of 10 nanoseconds pulse duration and to consecutively record a return pulse as reflected from the 70m-diameter footprint on the ground. GLAS systematically samples the energy returned from the surface as a function of time of flight, the so-called full waveform [1].

The applications of full waveform processing are increasing rapidly over the last years. ICESat data were recently used in land cover classification [3], forest species classification [5], estimating forest tree heights [7] and in assessing seasonal canopy differences [2]. Moreover, several research groups are developing methods for exploiting airborne full waveform laser altimetry data [6]. Essentially, the methods for processing space-borne and airborne laser altimetry data are the same. However, many problems in waveform processing are identified as well, but are not yet understood or are not yet automatically correctable. Possible error sources include instrumental changes, changing atmospheric conditions, surface moisture conditions, local snow cover, neglected canopy penetration rates and unresolved slope effects.

One way to identify such errors is to compare waveforms that cover the same footprint location. Waveforms obtained at the same location and at approximately the same time should be very similar. Meanwhile, seasonal or annual influences can be tracked and quantified by comparing overlapping waveforms from repeated campaigns. As can be seen from the campaign schedule in Fig. 1, bottom, these type of repetitions are all provided for by the ICESat mission. Waveform pairs within one epoch are obtained by considering crossovers between ascending and descending tracks, compare Fig. 1, top, were the ICESat tracks over Europe of the first measurement campaign in winter 2003 are visualized.

A unique contribution of this article is that for the first time a large database of tenths of thousands of repeated waveforms is presented that can be used to gauge a raw full waveform processing algorithm. This database will be used to answer the question: How can changes in waveforms from the same location be quantified and explained? A large benefit of choosing Europe as the Region of Interest is that many meta data are available to find explanations for inconsistencies as identified by the processing steps. This procedure is expected to result in a more robust waveform processing methodology to be used in e.g. future of-the-shelf processing of airborne full waveform laser altimetry and for the challenging task of processing large quantities of full waveforms over the polar regions.

The main research question that will be addressed in this article is as follows: 'How can changes in waveforms within one waveform pair be quantified and explained?' The focus of the research will be on waveform pairs from within one measurement campaign. In this case, waveforms should in principal be the same for all land cover classes. Differences may occur however because of not fully overlapping footprints, incorrect slope estimation, changing weather conditions or changing surface moisture conditions. It will be investigated if it is possible to determine correlation between nearby waveform pairs in the same land cover class in order to

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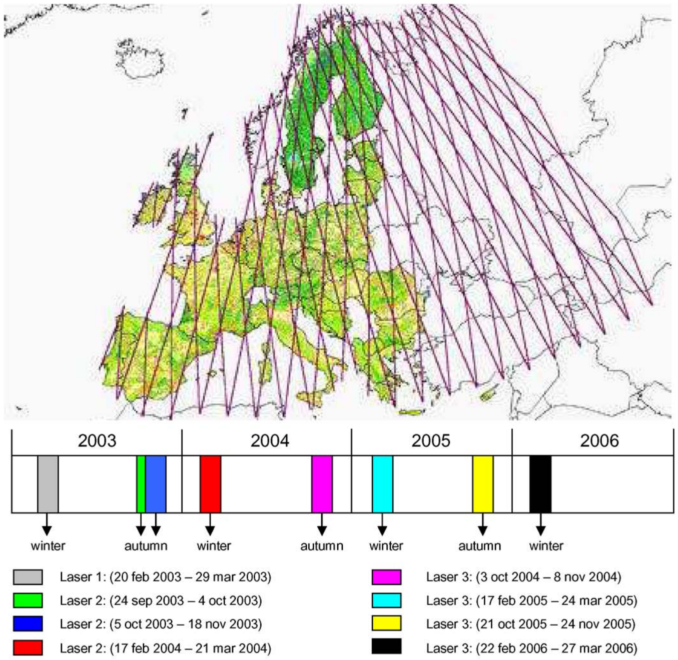

Fig. 1. ICESat campaigns, bottom, and ICESats tracks over Europe during the Winter 2003 campaign, overlaid on CLC2000 land cover data, top.

separate, identify and quantify these type of error sources.

In section II it is shown how to to obtain a database of overlapping waveform pairs from ICESat tracks as available over Europe. Moreover, parameters are introduced describing differences between waveforms. In section III the resulting database of waveform pairs is described. As a first application, three case studies of almost perfectly overlapping waveform pairs are discussed, before arriving at the conclusions

II. METHODOLOGY

A. Extraction of overlapping waveform pairs

Overlapping waveforms are extracted from the available ICESat full waveform data over Europe. The ICESat/GLAS system has acquired a large full waveform database since 2003 to 2006. Data of two campaigns (winter, i.e. February and March, and autumn, i.e. September, October, and November) each year (see Fig. 1, bottom, and Table I) are available from the National Snow and Ice Data Center. We identify two types of overlapping waveform pairs. A crossover pair consists of one ascending and one descending track waveform, Fig. 2, left, a repeated track pair consists of two waveforms of the same ascending/descending track but from orbits performed at different moments, Fig. 2, right. In both cases the footprint centers are within a threshold distance. This threshold is defined as the sum of the two half major axes of the two individual footprint ellipses, see Fig. 2, left.

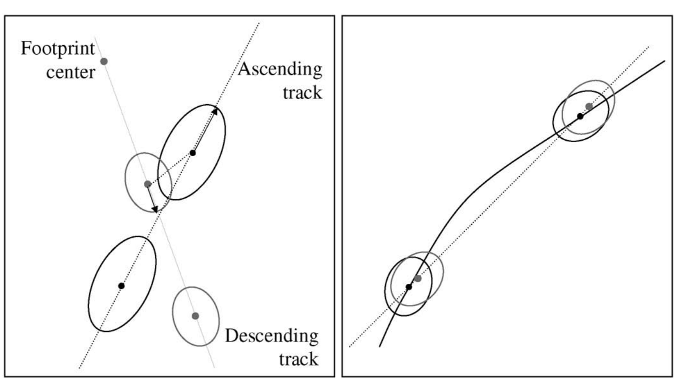

Fig. 2. Crossover pair, left, and two repeated track pairs, right.

In this research only waveform pairs from the same measurement campaign are considered. As a consequence, the time lag between the waveform pairs varies from a few days to a maximum of a few weeks. The procedure used to find waveform pairs is indicated in the flow chart in Fig. 3.

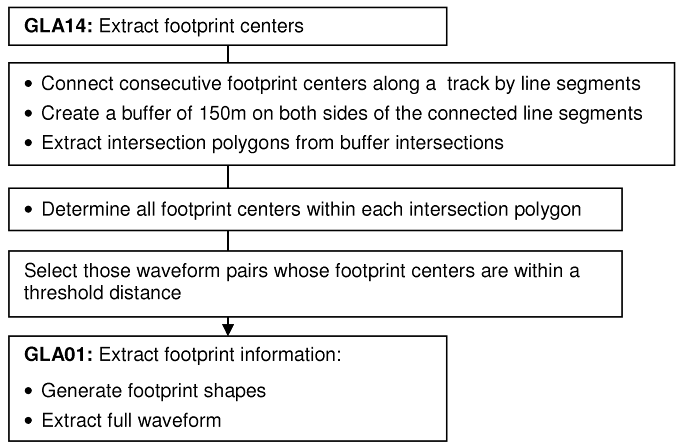

Fig. 3. A flowchart of finding crossover and repeated pairs

B. Waveform pair comparison

Before comparing the waveform pairs, some preprocessing steps are applied to individual waveforms. These steps are waveform calibration, i.e. conversion of relative units to absolute intensities, normalization and decomposition [2].

Waveform pairs were then compared by considering the differences of the following individual waveform parameters:
Median energy. The height of median energy $HOME$ [4] is defined as the distance from the peak of the ground return to the position of median energy of the fitted full waveform.
Waveform Extent. The waveform extent is the length of a waveform, $EXTENT$.
Relative energy. The relative waveform energy is defined as the received waveform energy divided by the emitted waveform energy, ER.
Moreover, the change in **intensity distribution** of both waveforms is considered by determining the mean squared difference, ΔI, in normalized waveform energy per bin, [2].

III. RESULTS AND DISCUSSION

A. Waveform pairs

In Table II the numbers of overlapping waveforms for eight epochs of European ICESat data are listed. In total a

TABLE I
ICESat EPOCHS, LASER NAME, ORBIT REPEAT PERIOD, ACQUISITION DATE, RELEASE, AND NUMBER OF POINTS

Ep.	Laser	Repeat (days)	Dates	Release	Number of points
1	1	08	02/20/03 - 03/29/03	118	496697
2	2a	08	09/25/03 - 10/04/03	426	287146
3	2a	91	10/04/03 - 11/19/03	426	1422863
4	2b	91	02/17/04 - 03/21/04	428	1056698
5	3a	91	10/03/04 - 11/08/04	428	1134105
6	3b	91	02/17/05 - 03/24/05	428	1153022
7	3d	91	10/21/05 - 11/24/05	428	1114930
8	3e	91	02/22/06 - 03/28/06	428	1097114

number of 113 955 waveform pairs were found. When actually determining the area of intersection of two waveforms, the size and orientation of the footprint ellipse has to be taken into account. Approximate footprint diameters are given as well. The distance between footprint centers is in general in the order of tenths of meters, but some waveforms exists for which the footprint centers almost coincide.

TABLE II
ICESat EPOCHS, TOTAL NUMBER OF PAIRS, INDIVIDUAL FOOTPRINT DIAMETERS, DISTANCE BETWEEN FOOTPRINT CENTERS AND NUMBER OF CLOSEBY WAVEFORMS

Ep.	Number of pairs	Footprint Diameter (m)	Distance (m) Min	Distance (m) Max	Waveforms <2m	Waveforms <40m
1	104809	95.0	0.20	95	60	15851
2	2450	83.1 - 90.2	18.51	88.20	0	626
3	2142	79.3 - 111.9	1.98	108.56	1	323
4	1170	81.6 - 103.7	2.76	98.41	0	289
5	64	19.7 - 22.7	2.65	21.30	0	64
6	2119	50.8 - 99.0	0.93	92.37	7	472
7	815	48.7 - 55.9	1.73	52.88	1	205
8	386	47.7 - 58.7	1.83	54.30	2	208

B. Differences between repeated waveforms

In Table III the average differences between the waveforms within the found waveform pairs are quantified, with respect to the waveform parameters as introduced in Section II-B. As expected the mean differences between waveforms within a pair are small, as both waveforms are obtained at approximately the same time and from the same location. The standard deviations of the differences are in most cases much higher. For one case this is illustrated in Fig. 4, where the histogram of waveform extend differences for waveform pairs from epoch 1 are given. Differences are ordered in the sense that always

TABLE III
DIFFERENCES BETWEEN REPEATED WAVEFORMS

Ep.	$\Delta HOME$ (m)	$\Delta EXTENT$ (m)	ΔER ($\times 10^{-11}$)	ΔI ($10^{-4}\times$J^2)
1	0.2 ± 4.8	0.5 ± 9.0	1.7 ± 18	5.3 ± 529
2	0.1 ± 2.1	0.9 ± 4.5	1.9 ± 6	2.4 ± 38
3	0.1 ± 4.6	0.6 ± 9.2	0.3 ± 21	0.5 ± 1
4	0.6 ± 15.8	0.4 ± 23.5	0.1 ± 21	0.2 ± 0.3
5	5.3 ± 17.7	7.5 ± 23.9	0.1 ± 24	0.8 ± 3.8
6	0.3 ± 10.1	0.6 ± 15.5	0.9 ± 25	7.6 ± 151
7	0.5 ± 16.2	0.4 ± 27.6	0.3 ± 26	0.3 ± 1
8	0.7 ± 18.3	1.7 ± 27.4	2.1 ± 32	7.0 ± 84

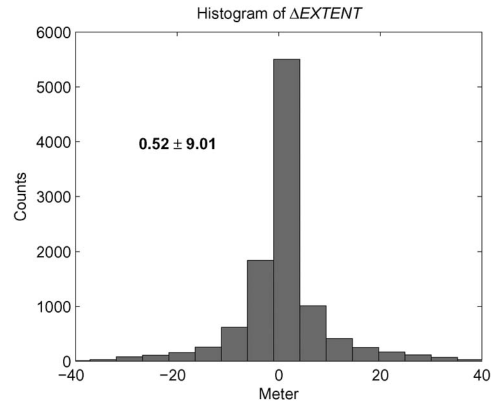

Fig. 4. Histogram of waveform extent differences of epoch 1.

the parameters of the more recent waveform are subtracted from the ones from the older waveform. No temporal trend can be observed but differences in waveform extent occur of up to 40m. Such differences can easily occur in areas with high buildings or steep rocks when the waveform footprints only partially overlap. More interesting are the many waveform pairs where only small differences occur. In a next step such pairs will be further analyzed to obtain possible relations with surface moisture changes, sea roughness changes or other more subtle changes that can be revealed by taking spatial correlation between changes into account.

C. Case study: coinciding waveforms.

Among the pairs of waveforms in the database some waveforms were found whose footprint centers where within 2m distance. As the acquisition time of these waveforms is almost coinciding as well, one would expect an almost perfect match between the waveforms. Here three cases are discussed were this reasoning does not hold true. In order to obtain insight into possible reasons for the unexpected differences in waveform characteristics, the three pairs under consideration are displayed in Fig. 5 on the top, while the corresponding footprints, overlaid on images from Google Earth, are shown in the bottom.

1) Case 1: The first waveform pair, Fig. 5, left, is located nearby the city of Cottbus, Germany. The distance between footprints is 1.69m. The acquisition date of the two waveforms differs by 16 days. The first raw waveform (cyan) shows a peak near the 340th nanosecond, that is absent in the second raw waveform (red). The location of this peak corresponds to a height above ground level of about 11m according to the GLA14 product. The Google image with the two similar and coinciding footprints overlaid, suggests that a small misregistration of the footprint locations can explain the difference in waveform: apparently, the cyan waveform partly covers the building on the left of the photo. According to GLAS documentation, [8], the horizontal geolocation accuracy (i.e. distance between true and estimated footprint centers) has a mean of 4.6m and a standard deviation of 9.3m.

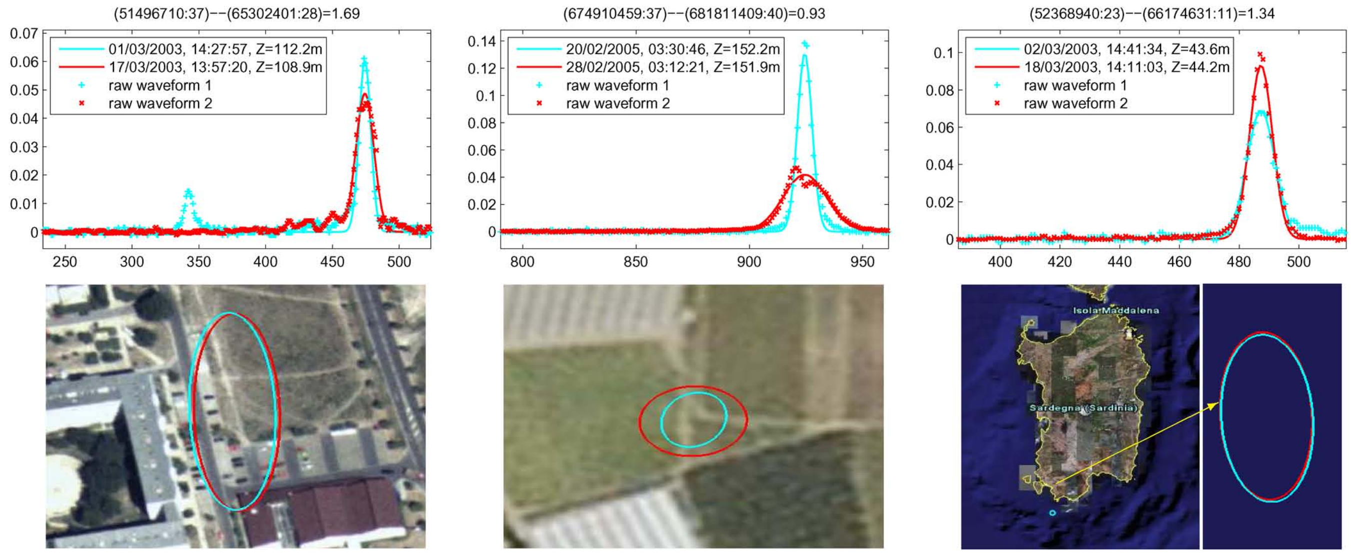

Fig. 5. 3 case studies with 2m distance difference between footprint centers: waveform pairs (top) and footprint pairs over images of Google Earth (bottom).

2) Case 2: The second pair is located in an open area in France. The distance between footprint centers is only 0.93m (see Fig. 5, middle). The extent of the second waveform (red) is wider than the extent of the first one (cyan). The wider waveform is displayed in red in the color image (bottom) and the other one in the cyan. These waveforms were acquired with a 8 day difference in 2005. The height difference between the waveforms is 30cm, (GLA14). The wider waveform has a larger footprint size. As a consequence it contains more reflections from low vegetation. As a result the waveform has a widened extent. In this case, the accuracy of the footprint centering is reported to be $2.9\text{m} \pm 3.7\text{m}$, [8].

3) Case 3: The third pair is located over sea, south of Sardegna island, Italy. The footprint locations are identical, the shape is quite similar, but the amplitude is clearly different, Fig 5. The first waveform has a larger peak intensity and a bit smaller waveform extent. The difference in acquisition date is 12 days and the GLA14 height difference is 60cm. The difference in waveform shape can be explained by changes in sea surface roughness or by changes in sea water parameters like temperature or sediment concentration. A rougher sea can result in a wider waveform and in a lower energy return.

IV. Conclusion

In this paper a database of more than 100 000 waveform pairs over Europe is introduced. This database consists of waveform pairs, acquired within a period of a few weeks with footprints that at least partially overlap. For all pairs within the database, changes in waveform parameters are computed, showing small average changes, but with a large spread.

The heterogeneity of the intensively used space, which has to be measured with respect to GLAS footprint spacing and size, limits the possibilities of a change detection based on single waveform pairs. Because of geolocation accuracy this definitely holds for built up areas and assemblies of small agricultural fields, found in many areas throughout Europe.

A case study of three almost perfectly overlapping waveform pairs suggests that this database can be used to address issues like misregistration, full waveform water roughness and low vegetation parametrization.

In a next step this database will be used to determine spatial correlation in subtle changes in waveform parameter values. It is expected that such a study will reveal new applications of full waveform space-borne laser altimetry.

Acknowledgment

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