ICESat full waveform database for land cover change detection over Europe

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Abstract – **ICESat laser altimetry data is a potential source for assessing land cover information. In this paper it is investigated how to obtain a database of crossover footprints from the ICESat laser altimetry data. The returned waveforms from these crossover footprints can then be used to detect land cover change. A method for finding these crossover footprints is introduced. Also waveform analysis is performed. A database has been obtained, using data from five different operation periods of ICESat containing 25847 pairs of crossover footprints in total. Nevertheless, there are still crossover footprints missing. Also there has been a contamination in the crossover footprints database with repeated track footprints.**

Index terms - **Full waveform, laser altimetry, ICESat, land cover change detection.**

I. INTRODUCTION

One of the applications of laser altimetry data is that it can be used for land cover assessment. Land cover assessment and monitoring of its changes are important for sustainable management of natural resources and environmental protection [1]. And when it comes to land cover changes one can distinguish between seasonal changes and more long term changes, for example due to the growth of an urban area or due to natural causes.

A potential source for applying the land cover assessment comes from a space mission that uses the laser altimetry principle: NASA's Ice, Cloud and land Elevation Satellite (ICESat) mission [2]. It has gathered a lot of laser altimetry data since the start of its mission in 2003. However, most data that is actually used in current research concentrates in areas around the poles. In this way, much data is unused, but not unuseful.

Therefore, in this study it is investigated how a database of crossover footprints from the ICESat laser altimetry data can be created, which then can be used to determine land cover change. The basic idea is then to compare returned waveforms

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from different time periods at the same spot on the earth. The area of interest is Europe, for three reasons:

- An area should be chosen that is widely subjected to seasonal changes (the ICESat mission has not been operating in a sufficiently long time period to state something about long term changes)
- The area should not be too small, as there are not that many crossover footprints.
- The area should also not be too large for data processing (though limiting to Europe will still take much data processing time).

To evaluate this way of determining land cover change is then to compare returned waveforms from the same time periods (which should be more or less equal) and by comparing with an existing land cover database, the CORINE land cover database [3].

The structure of this paper is as follows: in section II a review of the ICESat mission will be given, along with a description of the GLAS laser altimetry instrument onboard of ICESat and the data and software acquisition steps. After this, a method for finding the crossover footprints for the ICESat data will be introduced in section III. In section IV, as an application of the crossover footprint database, it will be investigated how the waveform characteristics of returned waveforms from the ICESat laser altimetry data can be used to determine land cover change at these crossover footprints. Section V will focus on the results of the method of finding the crossover footprints and. In section VI the results will be discussed and conclusions will be drawn. Finally, recommendations for further research are done in section VII.

II. THE ICESAT MISSION AND THE GLAS INSTRUMENT

In this section the ICESat's mission will be briefly described, after which the Geoscience Laser Altimeter System (GLAS), a space-borne LIDAR (*Laser Imaging Detection and Ranging*) instrument, will be discussed. First the scientific objectives of the ICESat mission will be handled in paragraph II.A. Then, the GLAS instrument principles will be dealt with in paragraph II.B. Finally, the data acquisition steps will be discussed in paragraph II.C.

A. The ICESat mission objectives

The scientific objectives of the ICESat mission, in summary, are [2]:

- Measure elevation changes of the Greenland and Antarctic ice sheets for the purpose of assessing:
  a) mass balance
  b) seasonal and interannual elevation variability
  c) elevation trends, and
  d) contribution to sea level rise
- Determine precise elevation topography and surface roughness of ice sheets and sea ice.
- Conduct global topographic measurements to contribute to topographic maps and digital elevation models as well as detect land elevation changes in excess of 1 meter per year in certain selected regions.

As a note, the ICESAT Mission itself is not without technical difficulties. Laser 1 was commanded to start firing on February 20, 2003. The March 29 failure of this laser resulted in a modified operating plan, which called for approximately 30 day operation periods, three times per year [4].

B. The GLAS instrument principles

The basic concept behind the laser altimetry principle used in ICESat mission can be explained as follows: The elevation of a spot on the Earth's surface illuminated by a space-borne laser is determined from the sum of two vectors: the position vector of the laser instrument plus the range vector (the position vector of the illuminated spot centroid with respect to the instrument, alternatively referred to as the altitude vector). The resultant vector is the position of the spot (or footprint), which can be readily transformed into geodetic latitude, longitude and height (or elevation) with respect to a reference ellipsoid. All the vectors can be explained by figure II.1. The fundamental data product consists of this geolocated spot and its surface arrival time (time tag) [4].
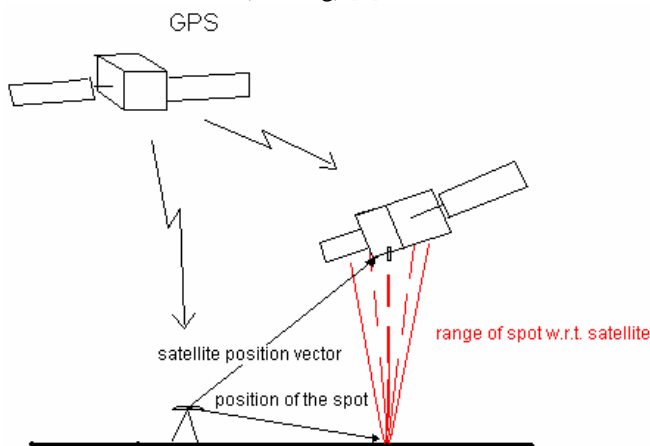

Figure II.1: Depiction of laser altimetry principles

Based on this principle, GLAS (onboard of ICESat) has three fixed nadir looking lasers (designated Laser 1, 2 and 3)

mounted on a rigid optical bench, with only one laser operating at a time. Each laser produces a 1064 nm pulse for altimetry and lidar, but a double crystal produces a 532 nm wavelength pulse, which yields a more sensitive determination of the vertical distribution of clouds and aerosols. The operating laser pulses at 40 Hz and the transmitted laser pulse illuminates a spot on the Earth's surface with a diameter of 65 m, except when optically thick clouds obscure the surface. Successive spots are separated on the Earth's surface by 172 m.

The footprints of the laser altimeter can be described as generally elliptical. Although the cause of this ellipticity is not specifically mentioned anywhere in technical documents concerning the GLAS-instrument, looking at figure II.2 taken from [5] one can see that the scanning mechanism used by GLAS is merely a simple mirror reflector (indicated with the red circle in figure II.2). Thus, one possibility to the cause of the nominal ellipticity is the combination of an oscillating mirror reflector (according to [6], a typical scanning mechanism used in laser applications) and the forward motion of the spacecraft. This implies that the ellipticity will be along-track, which is not the case as can be seen later.
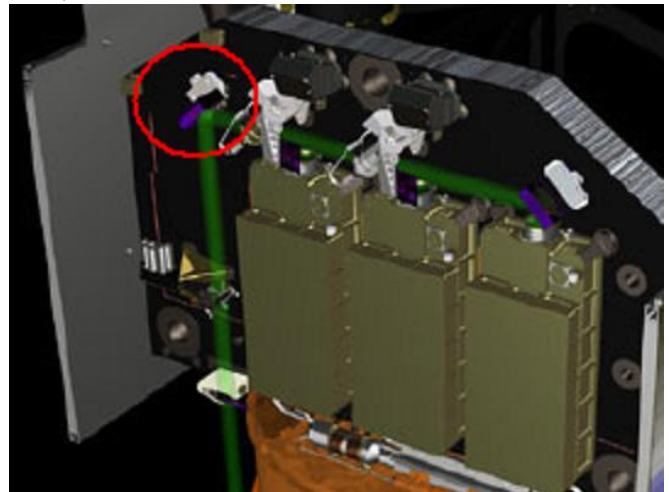

Figure II.2: The three GLAS-lasers and their scanning mechanism depicted.

However, as can be seen from figure II.3 in turn, the ellipticity seriously varies for different time periods.
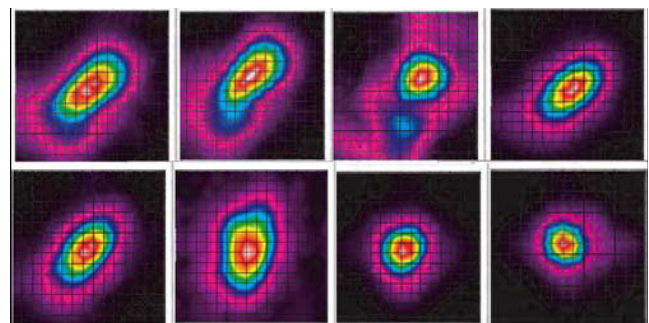

Figure II.3: Sample GLAS images of the laser far field patterns measured during different campaigns. (Top) Laser 1 (2/20/03), Laser 1 (3/4/03), Laser 1 (3/26/03), Laser 2a (9/26/03). (Bottom) Laser 2b (2/18/04), Laser 2c (5/18/04), Laser 3a (10/4/04), and Laser 3b (2/18/05) [7].

According to [7] this variation is mainly thought to be due to the changes over time in the spatial distribution of light from the laser diode pump arrays.

The echo pulse is captured by a 1 m diameter telescope and directed to an analog detector, then digitized by a 1 GHz sampler and stored along with a digitized record of the transmit pulse. Each pair of transmitted and corresponding echo pulses is then sent to the ground for analysis. These digitized pulses are referred to as laser waveforms. From the waveform data, the transmit time and the echo receive time are determined, from which the pulse time of flight (TOF) is computed. The one-way range, or magnitude of the range vector, is half the TOF multiplied by the speed of light. In addition, this one-way range is subjected to corrections, such as propagation delay in the troposphere [4].

In this way GLAS has provided a view of the Earth in three dimensions with unprecedented accuracy. Although the primary objectives focus on polar ice sheet mass balance, the GLAS measurements, distributed in fifteen science data products, of which the first (GLA01) and the fourteenth product (GLA14) were used in this study, have interdisciplinary application to land topography, hydrology, vegetation canopy heights, cloud heights and atmospheric aerosol distributions [8]. Specifically, the GLA01 includes the transmitted and received waveform from the altimeter, while the GLA14 includes land surface elevations, laser footprint geolocation and reflectance, and geodetic, instrument, and atmospheric corrections for range measurements [8]. In this case, only the laser footprint geolocation was needed.

C. ICESat data acquisition

Before data processing can begin, the required data should be acquired, together with some programs. The following three steps need to be done:

1. Ordering the appropriate ICESat data subset from [8], which in this case is the GLA01 and GLA14 dataset over Europe (see figure II.4 for the satellite ground tracks).
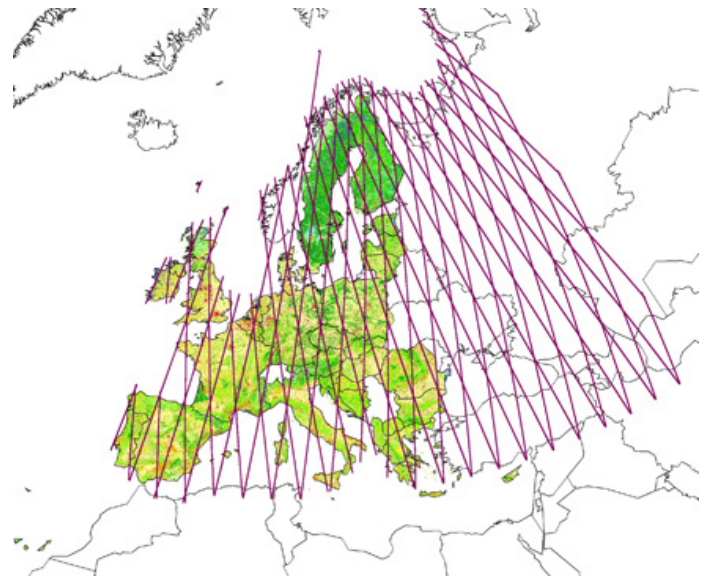

Figure II.4. Map of area of interest (10W, 55E, 35N, 75N). Shown are also the satellite ground tracks for epoch 1, and the CORINE land cover database.

The files are in binary and are the newest possible releases. A timeline for the ICESat data is displayed in figure II.5.

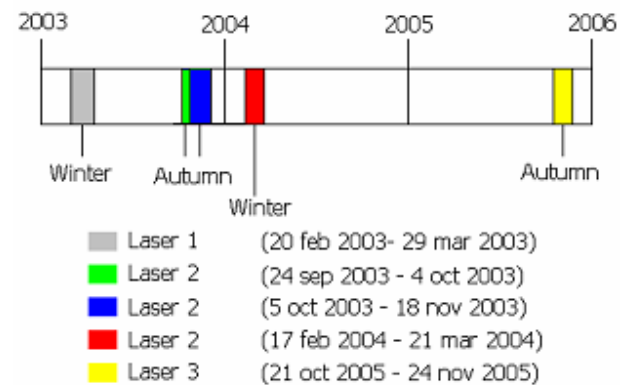|		
Laser 1	(20 feb 2003 - 29 mar 2003)
Laser 2	(24 sep 2003 - 4 oct 2003)
Laser 2	(5 oct 2003 - 18 nov 2003)
Laser 2	(17 feb 2004 - 21 mar 2004)
Laser 3	(21 oct 2005 - 24 nov 2005)

Figure II.5. Timeline of the ICESat data

2. Once the ftp link is received by e-mail, downloading the appropriate data can begin. The data in this case however required extensive hard disk space (17Gb), so this should be taken care of before downloading can begin

3. Downloading the appropriate tools for processing the GLA01 and GLA14 (see table II-1).

Table II-1. Data processing tools used plus a description

Tool	Description
IDL ellipsoid conversion [8]	Converts between GLAS and WGS-84 ellipsoids
IDL GLAS readers [8]	Reads data from an ICESat/GLAS file and prints all the variables in ASCII format. The readers run under IDL (6.1 or greater) or the free IDL Virtual Machine (IDLVM).
NSIDC GLAS Altimetry elevation extractor Tool (NGAT) [8]	Extracts elevation and geoid data from GLAS altimetry products (GLA06 and GLA12-15) and outputs latitude, longitude, elevation, and geoid in ASCII columns. The NGAT runs under IDL (6.1 or greater) or the free IDL Virtual Machine (IDLVM). In this case, used primarily for converting the GLA14 files from binary to ASCII format
IDL Virtual machine [10]	The basic conversion and imaging program used. The Virtual Machine is a free version of IDL.
Arcview GIS 3.2 [11]	Program used for imaging the satellite tracks over the area of interest contained in GLA14.
Matlab 7.1[12]	The main program used for programming and conversion. Requires license.

III. METHOD FOR FINDING CROSSOVER FOOTPRINTS

In this section a method of finding crossover footprints will be introduced. First of all, it has to be defined what the desired information is, this is described in paragraph III.A. Then, in paragraph 0 it is discussed how to extract points and how to use them. After this, in paragraph III.C, based on the preparation work the points are used to create intersection neighborhoods. These intersection neighborhoods are subsequently used to extract footprint information in paragraph III.D. Finally, this footprint information is used to do a check for overlapping footprints in paragraph III.E.

A. Desired information

To start off, a definition of a crossover footprint must be given: a crossover footprint is basically a footprint which is overlapped by another footprint, one from a descending ground track and the other from an ascending ground track. So the locations of these crossover footprints are around intersections of ground tracks. An example of two overlapping crossover footprints is given in figure III.1:
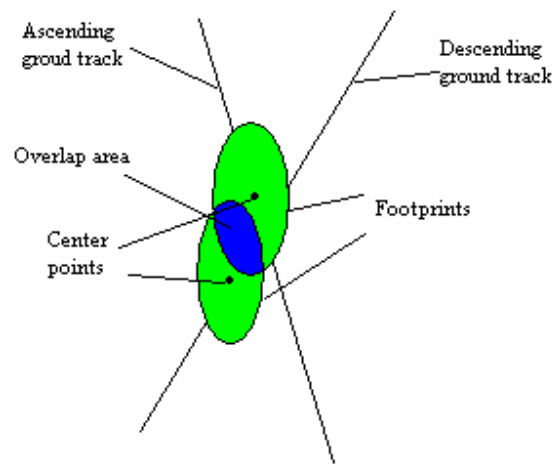

Figure III.1. An example of two overlapping crossover footprints.

As can be seen from this figure, there are two parameters desired for the overlapping crossover footprints:

- The location of both of the center points of the footprints
- The size and shape of both of the footprints

These two parameters can then be used to determine statistics of the footprints, e.g. the overlap area of the footprint and the distance between the two center points.

Finding these crossover footprints takes much processing time (in the order of a week), since there is a lot of data. The stepwise flow structure to acquire these points is shown in figure III.2.
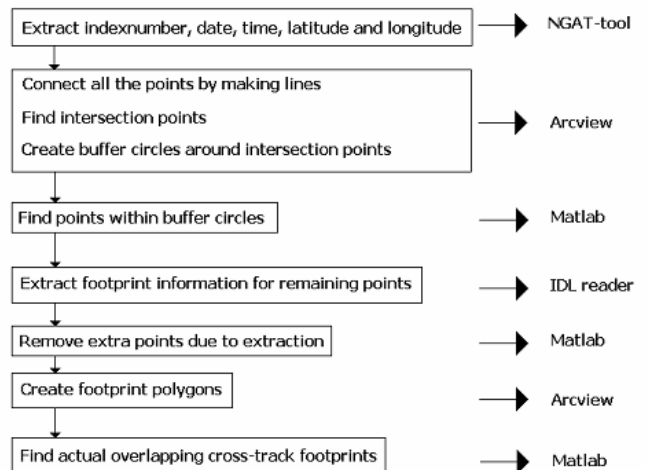

Figure III.2. The flow structure to find the crossover footprints

B. Point extraction

For finding crossover footprints for ICESat data, one only needs to use the GLA14 data product. The relevant GLA14-parameters are displayed in table III-1.

TABLE. III-1. RELEVANT PARAMETERS FROM THE GLA14-DATA PRODUCT WITH A DESCRIPTION AND UNITS

Parameter	Description	Units/format
Index number	Every second (consisting of 40 shots per second) of data gathered by GLAS has its own unique index number	NA
Shot number	Every index record contains 40 shots of 25 ms.	NA
Date	Date in the Julian calendar	[mm/dd/yyyy]
Time	UTC Time up to millisecond accuracy	[hh:mm:ss]
Latitude	The latitude of the illuminated center point on earth of the sent pulse in the GLAS-reference system	[deg]
Longitude	The longitude of the illuminated center point on earth of the sent pulse in the GLAS-reference system	[deg]
Azimuth angle	The orientation of the major axis of the footprint w.r.t. the north	[deg]
Major axis	The major axis of the footprint	[m]
Minor axis	The minor axis of the footprint	[m]

The first step is then to extract the GLA14 data with the NGAT-tool discussed in section II.C. In this way one only gets the index number, date, time, latitude, longitude and two other irrelevant parameters (the elevation w.r.t. to the theoretical Earth ellipsoid and the geoid height, respectively), for each shot in the dataset.

Now, all these points for all the five epochs can easily be displayed in one picture using arcView (this only requires latitude and longitude). With arcView it is then possible to "draw" a line between all the points (figure II.4 is an example of those lines). After that one is able to find each intersection point between the lines.

C. Intersection neighborhoods

The next step is then to create intersection neighborhoods. In practice they are drawn as circles (with arcView these so called buffer zones are actually approximated as polygons). The points of interest of the two crossing tracks within those circles can then be subset. The circle radius used is then set to 500 meters. In this way maybe some useful points are lost, but

nevertheless this needs a minimum angle δ between two ground tracks which can be calculated from the geometry of figure III.3:
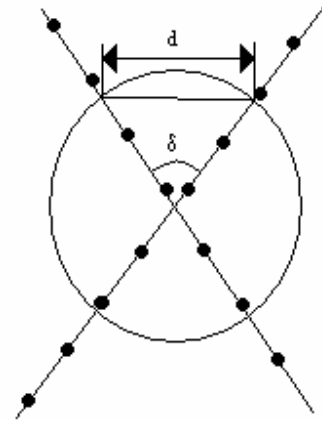

Figure III.3. Buffer zone circle and two crossed tracks illustrated.

If one assumes the maximum distance for two footprints to overlap each other is 100 meters, then the angle delta follows as:

$$\delta = 2 \cdot \arcsin\left(\frac{100/2}{500}\right) = 11.5°$$

This is a small angle, considering the fact that ground tracks at crossovers cross each other almost everywhere with a larger angle, so not many useful overlapping points are lost. Another consequence of this step is that one actually gets some points of a repeated ground track. This is due to intersection of two repeated tracks due to orbital and/or positioning errors (for example, the solar arrays of ICESat cause a 1-hz oscillation, which in turn causes the footprint on earth to oscillate tens of meter crossover) [7]. One could imagine this as displayed in figure III.4.
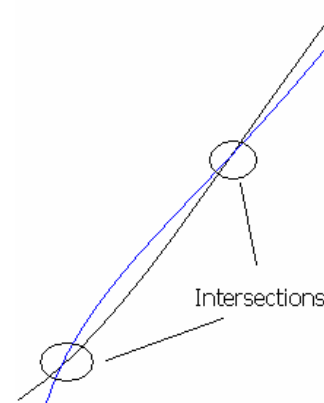

Figure III.4. Intersection of two repeated tracks due to errors (exaggerated and not to scale).

The last thing is then to make one polygon of overlapping circles (this is for practical reasons useful, since otherwise there would be duplicate points when subsetting the points within the buffer zones).

D. Footprint information extractor

The third step is to use Matlab to subset the points within the buffer zones. For every buffer zone (polygon) it is then checked which points are in it by using the INPOLYGON command of Matlab. This step is visualized in figure III.5.
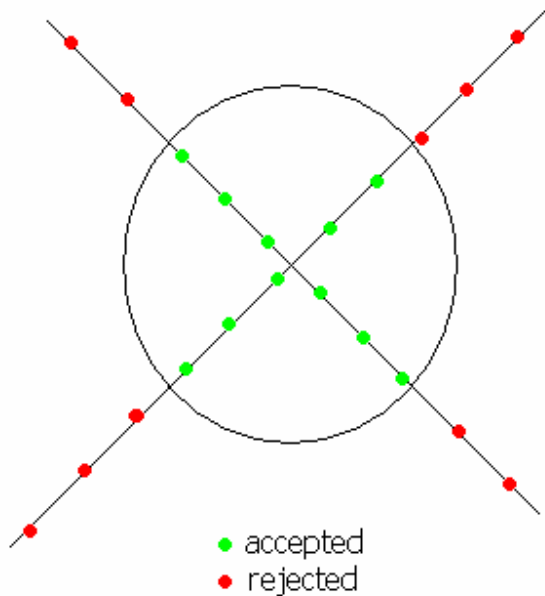

Figure III.5. Subsetting of the points within the buffer zones (not exactly to scale).

As one can see from figure III.5 there are small 'line segments' which are subset (in this case two line segments, one of five and another of six points). These line segments are actually used to convert pieces of the GLA14 data product with the IDL readers as discussed in section II.C. This is done by the timestamps of the first and the last points of the line segments. After that, what needs to be done is to convert the date and time of those points into the J2000 time reference system, which is the time system used in both the GLA01 and GLA14 products. When doing the extraction step one has to take an extra second into account, because the IDL-reader actually compares with the timestamp of the first shot of the index-number and always picks the start time which is after the given start time (this is a limitation of the IDL readers). Now, one can extract all the information needed for all the points, as displayed in table III-1, so footprint information is now available as well, which is important when determining 'actual' overlapping footprints.

E. Overlap check

The footprints information is now available, however the step of the check for the buffer zones must be redone, since there are also points outside the buffer zones again due to the limitations of the IDL readers and to add information of the buffer zone in which these points are (each buffer zone has its

own unique number). One also has to remove duplicate points due to the limitations of the IDL reader as discussed before (imagine two line segments which are close to each other and by adding one second, these line segments overlap each other).

The next step is to use arcView again. For each point, a footprint can be created based on the major axis, minor axis and azimuth angle of the major axis. For each point within each of the five epochs it can be checked whether footprints overlap each other and it is here that the information of the buffer zone is of big importance, since checking every other footprint with every footprint would take a lot of processing time.

Finally, for every point within the same buffer zone it is checked whether footprints overlap each other. And now one has to distinguish between comparing within the same epoch and in comparing with an other epoch, e.g. an epoch 1 point is first checked with and epoch 1 point within the same buffer zone and then an epoch 1 point is checked with an epoch 2 point within the same buffer zone and so on.

IV. RETURNED WAVEFORMS AT CROSSOVER FOOTPRINTS

In this section, it will be investigated how the returned waveforms at the crossover footprints can be used to determine land cover change. First, in paragraph IV.A waveform analysis will be explained. Then, in paragraph IV.B it will be investigated how to use these waveform characteristics for determining land cover change. This section follows closely from [9].

A. Returned waveform analysis

One of the principal objectives of the ICESat mission is to measure land topography profiles referenced to a global datum, and the height of vegetation canopies. [9] In this study, emphasis is put on the last two objectives, in order to carry out a full waveform analysis for land cover detection change.

The received waveforms can be found in the GLA01 data product. This can be done with either an extraction of all the GLA01 information or with a direct extraction of the waveforms. This depends on whether the waveform is compressed or not, see [9] on how to check whether the waveforms is compressed or not. The raw received waveform is then in voltage units and consist of a time span of 544 ns.

To perform waveform analysis, the raw waveforms as extracted from the GLA01 data is assumed to be a sum of Gaussian components as in eq. 1.

$$w(t) = \sum_{n=1}^{P} W_n(t) \qquad \text{eq. 1}$$

In which P is the number of components, w is the fitted waveform and W_n is an individual Gaussian component corresponding to component n which is given by eq. 2.

$$W_n = A_m e^{-\frac{(t-t_m)^2}{2\sigma_m^2}} \qquad \text{eq. 2}$$

With A_m the amplitude, t_m the time at which the mean value occurs and σ_m the standard deviation. The idea is now to find these three parameters describing the Gaussian component for each individual component, such that it fits the raw waveform best.

First the raw received voltage waveform is normalized by dividing by the total received energy, so that the area under the waveform graph equals one. This step can be described by eq. 3:

$$w_{norm} = \frac{w(t)}{E_{tot}} \text{ with } E_{tot} = \sum_{i=1}^{m} w_{t_i} \cdot \Delta t \qquad \text{eq. 3}$$

Where W_{norm} is the normalized waveform, E_{tot} is the total received energy, w_{ti} is the received voltage at time t_i, Δt is the sampling interval determined by the sampling frequency of the received signal (1 GHz) and m indicating the end of the waveform. This step is needed to compare different received waveforms, since the energy sent is not always the same.

The next step is then to use the least squares approach to determine the parameters for the individual components and the number of individual components. This of course is a nonlinear problem, but one could solve for it by iterative linearized least squares methods.

The procedure is to first compute the iterative least squares solution assuming one component, computing the least squares residuals vector e, using the squared sum of these residuals ($e^T e$), and is then used to decide whether another component is in the waveform. One can do this until the squared sum of the residuals becomes small enough.

Now, there are four parameters of importance for land cover change detection methods:

- Number of modes: The number of Gaussian components found in the waveforms.
- Total received energy. This can be calculated by calculating the area under the graph from the start of the actual waveform, until the end.
- Begin waveform: Location where a waveform first rises over the threshold value (this value is determined from the noise contained in the waveform, see [5] for more details).
- Width of the waveform: this is determined by the time between the beginning of the waveform and the end of the waveform.

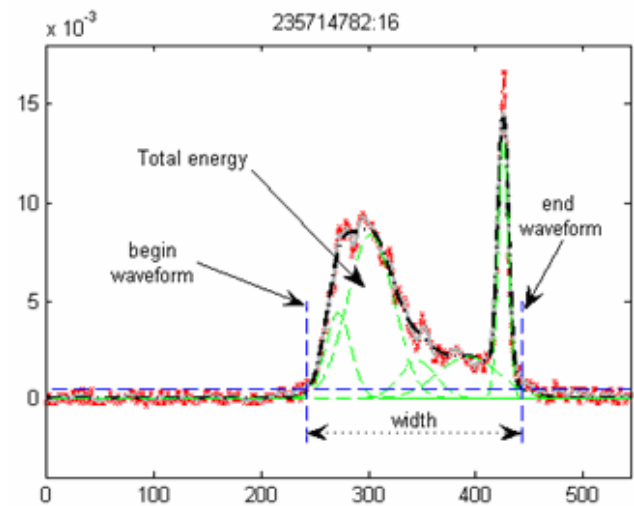A visual explanation of these parameters can be seen in figure IV.1.

Figure IV.1: A typical waveform indicating important waveform parameters.

Next, the waveforms can be classified into classes based on the above parameters, accordingly: a body of water, bareland, low vegetation, high vegetation, or urban.

Water absorbs most of the laser energy, which gives a lower total energy to the received waveform in comparison with the three other classes. Bareland in turn usually returns an easily identifiable uni-mode, one peak waveform. Low vegetation can in turn cause multiple peaks in the waveform, but with a limit of maximum 2 extra peaks with low amplitudes.

The complexity of the received waveform rises in the case high vegetation and urban areas, due to the often complicated areas and height differences of these classes caused by artificial objects and high trees. This usually means multi-form (several peaks), and wide, received waveforms. The difference between the two classes usually manifests itself through width differences in the peaks. For example, high vegetation can be differentiated from urban areas by comparing the width of the first peak in the waveform; the tree crowns usually cause the first peak to widen in w.r.t. to its urban counterpart, and generally all the urban waveform peaks are narrower than that of high vegetation, due mostly to the sharp artificial edges of e.g. buildings.

More specifically, the wider the first peak of the high vegetation, the earlier the first rising edge of the waveform will obviously occur. Thus in practice, by determining the first rising edge of the waveform, one can distinguish between high vegetation and urban areas. An example is given in figure IV.2.
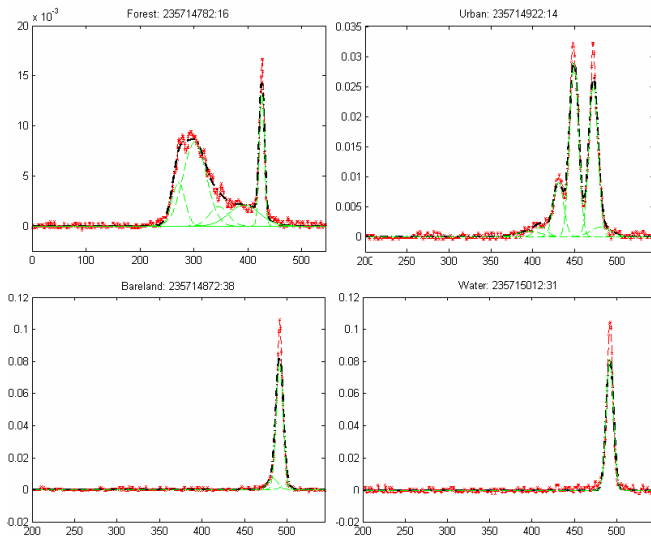
Figure IV.2. Top Left: High vegetation. Top Right: Urban. Bottom Left: Bareland or low vegetation. Bottom Right: Water. [9]

Additionally, the surface from which the waveform scatters back, has an effect on the overall waveform shape. The main factors in this are surface roughness and slope (see figure IV.3). Both cause a considerable widening of the Gaussian components in terms of standard deviation, resulting in with generally the same amplitude as an undistorted waveform Gaussian component, but noticeably wider. Furthermore, the effects of slope and roughness can be parameterized and even measured, so as to determine the slope and roughness from the waveform itself.
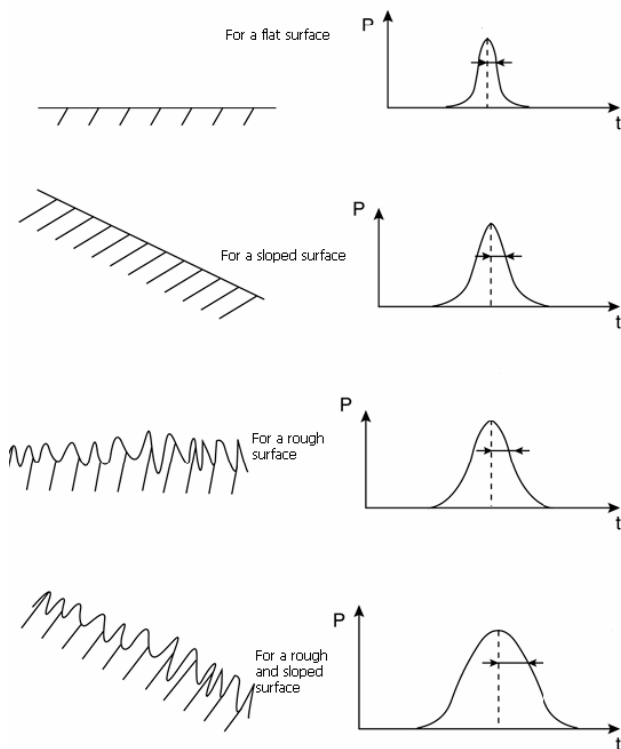

Figure IV.3: an example of surface effect on waveform.

B. Determining land cover change

The database of the crossover footprints can now be used to determine land cover change. The idea is then to look at the returned waveforms from an overlapping pair of footprints. The difference should then say something about land cover change. This idea is visualized in figure IV.4
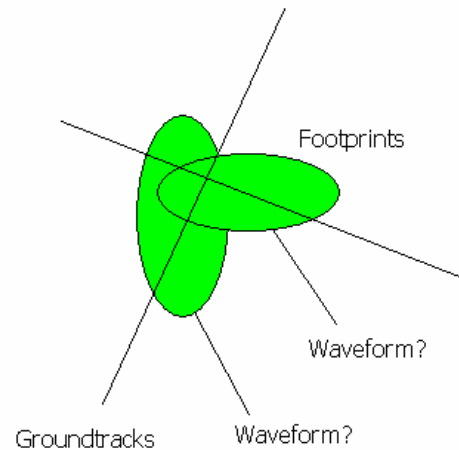

Figure IV.4. Comparison of footprints

Further, the whole Europe area will not be used, because data processing of the waveforms takes much processing time. In this case it will be limited to two areas:

- An area in Finland, between 60° – 64°N and 24° – 28°E.
- An area in Spain, between 40° – 44°N and 2° – 6°W.

V. RESULTS

In this section the results of both the obtaining of the overlapping crossover footprints and the method of determining land cover change as an application of finding these crossover footprints is given. First, the database of overlapping crossover footprints is discussed in paragraph V.A. Then the results of the returned waveforms are presented and discussed in paragraph B.

A. Crossover footprints database

With the method of finding crossover footprints one can find a number of overlapping footprints as displayed in table V-1.

TABLE V-1: AMOUNT OF CROSSOVER OVERLAPPING FOOTPRINTS.

Epoch	1	2	3	4	5
1	610				
2	2563	158			
3	1598	1079	1334		
4	484	528	4438	176	
5	843	553	7915	3062	506

Note that the diagonal here represents the amount of points which for overlapping footprints within the same epoch.

Also important parameters for the overlapping crossover footprints is the overlapping area between two points and the distance between the two center points, as it can say something about quality equality of circumstance (laser backscatter from the same spot on earth). In table V-2 the average percentage in terms of maximum overlap area between two footprints is shown (the average footprint size for each epoch is used for this, so this percentage is the ratio between the average overlap area and the maximum overlap of the average footprint):

TABLE V-2: AVERAGE OVERLAPPING AREA IN PERCENTAGE OF MAXIMUM OVERLAP BETWEEN TWO FOOTPRINTS.

Epoch	1	2	3	4	5
1	26.7%				
2	24.1%	21.8%			
3	32.4%	29.9%	34.8%		
4	20.2%	44.9%	22.6%	18.0%	
5	34.4%	36.3%	39.2%	41.7%	23.6%

In table V-3 the average distance between two center points of footprints is shown.

TABLE V-3: AVERAGE DISTANCE BETWEEN CENTER POINTS OF FOOTPRINTS IN METERS.

Epoch	1	2	3	4	5
1	44.4				
2	52.1	45.6			
3	49.7	46.9	51.4		
4	48.7	31.4	43.5	45.0	
5	40.6	36.6	41	35.1	32.2

In figure V.1 all the points of the first epoch within the crossover footprints database are displayed:

Figure V.1. All the points of the first epoch within the crossover footprints database.

B. Land cover detection change

In figure V.2 the result of a large overlap between two footprints from the same epoch 3 and one from epoch 5 is shown within the Spain area.
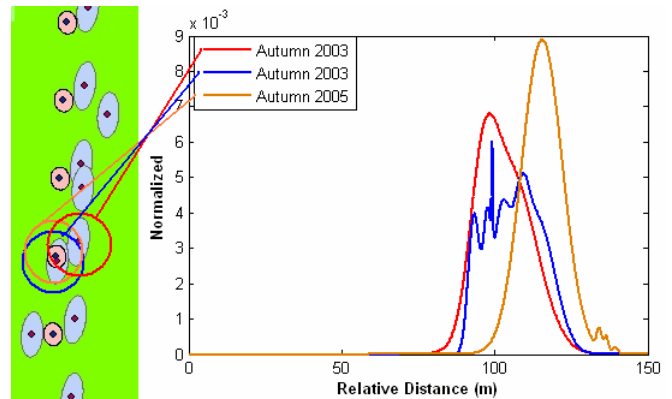

Figure V.2. The overlap between two footprints from autumn 2003 and one footprint from autumn 2005, within the Spain area

In the left side of this figure the footprints can be shown. It shows the crossing area as well as the CLC2000 background (green, forest). From this the ground tracks can become clear too, although this is a combination of two repeated tracks and one crossing track. Note that the footprints from autumn 2003 and autumn 2005 have a large overlap, so they should have had almost the same returned waveforms when there was no land cover change and equal other circumstances such as cloud thickness. The size and shape of these footprints also show a correspondence to the discussion of the footprint size and shape as in section II.B.

In the right side of figure V.2 the corresponding three returned fitted waveforms are shown. According to the CLC2000 land cover database this is a forest area, which might well be the case when looking at the three fitted waveforms, although the large ground peak is missing compared to the typical returned waveform for a forest area as described in section IV.A.

The difference between the two fitted waveforms from both autumn 2003 seems to be due to some 'unremoved' noise within one of the returned waveforms. The difference (or perhaps change) between the two waveforms from different epochs seem to be some sort of a shift, which could be an effect of clouds.

Next, there is also a figure from the Finland area, from which the location can be classified as forest. This one is displayed in figure V.3.
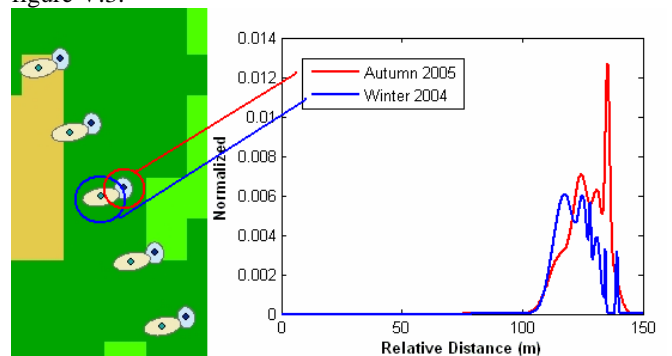

Figure V.3: The overlap between two footprints from winter 2004 and autumn 2003 within the Finland area.

From this figure it can be seen that there is not so much overlap, but according to the CLC land cover database they would be classified the same, a coniferous forest. So the returned waveforms should be more or less the same, or then experience changes due to land cover or seasonal changes.

It can also be seen that there is less backscatter from the ground (the last peak in the graph) in the returned waveform from epoch 4 (winter 2004). This is maybe due to the fact that the emitted laser pulse can not reach the ground that well, because it may be 'blocked' by snow on top of the trees.

Additionally, it can again be seen that the footprints size and shapes for this figure show correspondence to the discussion about footprint size and shape as in section II.B and that they disprove the idea of the ellipticity in the along-track direction, because the ellipticity is more in the across-track direction.

The next figure (figure V.4) is from the Spain area again (off the north coast of Spain) and its location can be classified as water.
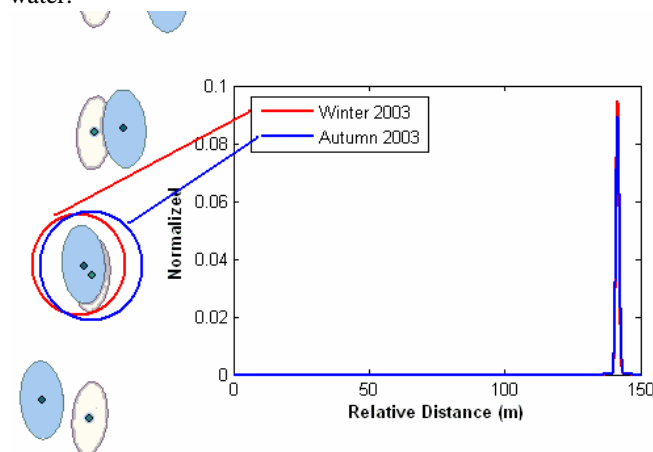

Figure V.4: The overlap between two footprints from winter 2003 and autumn 2003 within the Spain area

From this figure it can be seen that these returned waveform are very much overlapping each other (they are almost the same). The main reason for this is that water almost everywhere on earth has the same returned waveform, when the same atmospheric circumstances are the same, e.g. wind, clouds. It is not so dependent on its location (although in this particular example there is a large overlap between footprints so the locations are quite equal).

VI. CONCLUSIONS AND DISCUSSION

In this section it will first be discussed how good the database product for the overlapping footprints is, in paragraph VI.A. Then, in paragraph VI.B, missing ground track points in the dataset will be discussed. Finally, the results from the land cover detection change will be reviewed in paragraph VI.C.

A. Quality of crossover footprints database

Although 25847 pairs of crossover footprints were found, not all of them were found, mainly for three reasons:

- There are ground tracks at crossovers, which are intersecting each other with an angle smaller then 11.5°.
- Some crossover points are missing due to thick cloud cover. This is discussed further in paragraph VI.B.
- Footprint orientation information was not proper, so a circle with a diameter of the minor axis was taken to still be able to create an approximate footprint

Also there is a 'contamination' of repeated ground track footprints with the crossover footprints database due to the orbital errors in the repeated ground tracks. These contaminations could be seen as long streaks of crossover points with timestamps all from within a small time period.

In table VI-1 the total number of points within the five datasets together with the total number of points left in the crossover footprints database is shown in order to give an indication of the total of number of points 'removed' with the method for finding crossover footprints.

TABLE VI-1: TOTAL NUMBER OF POINTS IN THE DATASET TOGETHER WITH THE TOTAL NUMBER OF POINTS IN THE DATABASE.

	Total number of points	Points in crossover database	Percentage of all points in database
Epoch 1	1993840	6708	0.34%
Epoch 2	566269	5039	0.89%
Epoch 3	2449003	17698	0.72%
Epoch 4	1832752	8864	0.48%
Epoch 5	1941357	13385	0.69%

B. Missing ground track points due to cloud cover

According to [4], "The operating laser pulses at 40 Hz and the transmitted laser pulse illuminates a spot on the Earth's surface with a diameter of about 65 m, except when optically thick clouds obscure the surface". Furthermore, the GLAS altimeter channel penetrates optically thin clouds. Although the results vary with time and location, approximately 60% of the transmitted pulses over, for example, Antarctica have recorded surface echo pulses [4], while the percent of missing ground track points over Europe is not determined yet. This could be determined by, for example, estimating the total length of the line segments within the Europe area and then dividing by the distance in between the center points (which is 172 m). The percentage of missing points could then be acquired by dividing the points which are in the dataset divided by this estimated theoretical maximum number of points.

Depending on the nature of the clouds (particle size and altitude), a forward scattering effect can introduce a bias [13].

Additionally, the GLAS manual [14] explains that, "Heavy clouds, (optical depth > 2 km) will completely block returns, while thinner clouds and aerosols cause forward scattering, which distorts the waveform, thereby shifting the centroid of the return pulse (and of fitted Gaussians) to later times."

Complementary to these, an illustration is given in the figures below (figure VI.1, VI.2 and VI.3.)
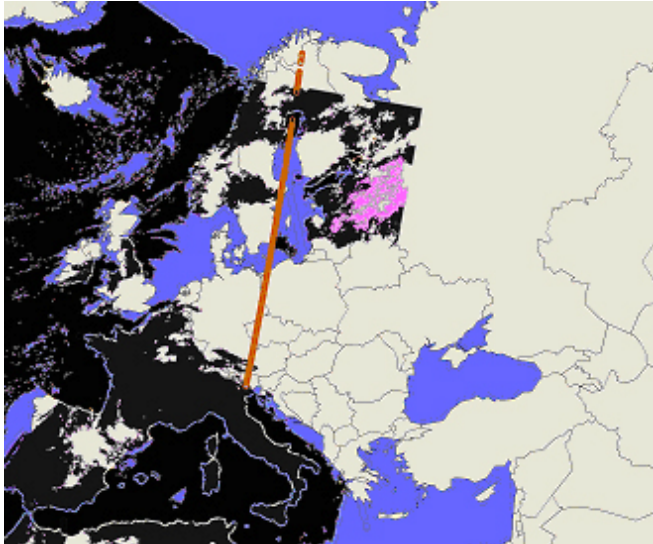

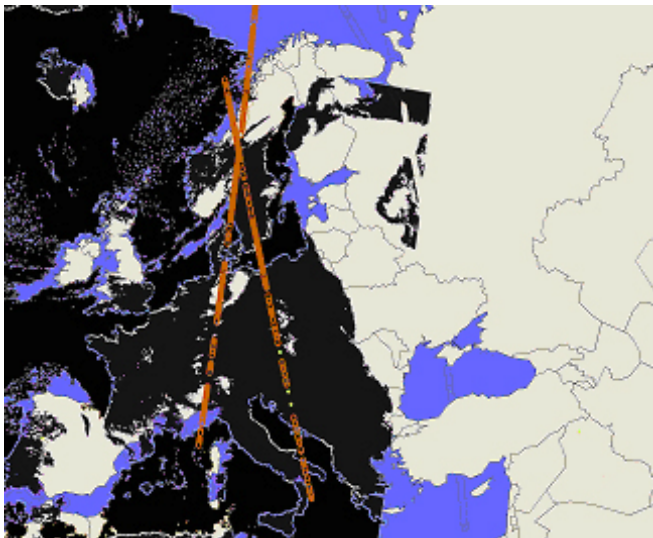Figure VI.1. February 21, 2004

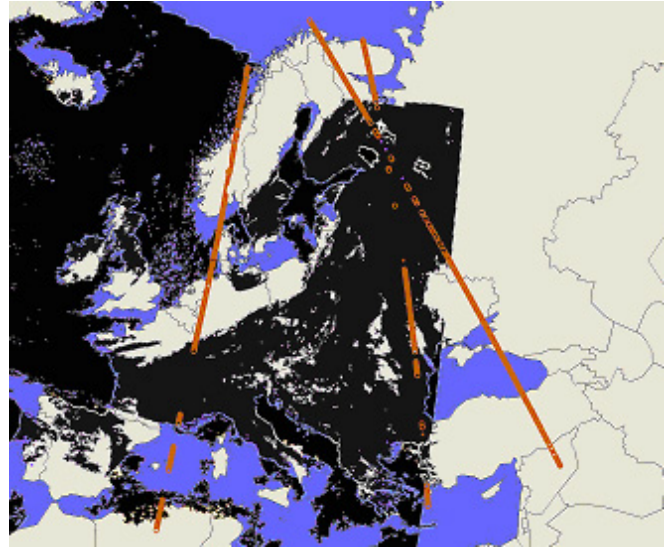Figure VI.2. February 22, 2004

Figure VI.3. February 23, 2004

The color scheme used in the picture can be explained as follows: black represents cloud coverage, white is for clear skies over land, blue for clear skies over water bodies, pink for rain, and the brown lines are the series of ground track points created that day. Take note how the ground track series is often either severely patchy or completely missing over cloud covered areas.

These pictures are not to be taken as precise, but merely to show a tentative visualization of a relation between missing ground track points and cloud cover. They were created by simply overlaying crude cloud coverage pictures taken by the US National Oceanic and Atmospheric Administration (NOAA) [15] with the ground track points from the same day.

Also as a note, figures VI.2 and VI.3 include ground track series outside the time span (6 to 8 hours) during which the cloud coverage was recorded, because the NOAA cloud coverage recordings at the time of these extra tracks show that the cloud positions haven't changed significantly and thus the series could be included for the sake of maximum visualization.

So in general, one can say that cloud cover interferes with laser altimetry measurements to a significant level, and that cloud cover is a necessary but possibly not a sufficient condition for causing this interference.

Possible other cloud-based factors that can influence laser altimetry are cloud albedo (a measure of the reflectivity of a cloud; this can be seen through infrared [16], as optically thick clouds tend to have a higher reflectance and show up in visual infrared as colder than their surroundings), which might affect the scattering of the laser measurements. Additionally, based on observations made during this study, integrated water vapor might also quantitatively correlate with the scattering effect of the cloud cover on the laser measurements. Further, the power output of the laser beam might not be enough for a received signal, as the power output of the lasers dropped continuously [7] from the start of the ICESat mission.

C. Land cover detection change at crossover footprints

Although there is quite some correlation between returned waveforms, it is very difficult to really state something about land cover change. When the land cover classification changes, it could also be due to errors in the returned waveform. Also the classification method used has an accuracy of 73% [9], so when looking at two footprints there is only a chance of 53% that they are both classified correctly. Improvement in the classification method (for example taking cloud thickness into account) might improve this accuracy of the classification method. Also by averaging out a lot of waveform data would improve the classification, which is an indication the importance of this database.

Furthermore, we noticed that for the Finland area there were a lot of corrupted return waveforms, whereas for the Spain area there were less corrupted waveforms. Possibly this is due to thin cloud cover over Finland, as Finland is maybe often more cloudy than Spain. Also terrain roughness and snow could cause these errors in the Finland area.

VII. RECOMMENDATIONS

Based on this study a few recommendations can be done in further investigating this method. First of all, returned waveforms of repeated ground tracks and how they can be used effectively, is discussed in paragraph VII.A. Then, a comparison of incorrect waveforms and cloud cover is briefly done in paragraph VII.B.

A. Returned waveform at repeated ground tracks

During this case study, waveforms from different epochs were compared by focusing on the footprints at the crossing of two ICESat tracks. This would create crossovers on several spots over the planet surface, and a whole pattern the surface in due time, from which an area of interest could then be analyzed.

However, it was found during the analysis process, that a more effective method would be to use repeating orbits for waveform comparison. In other words, the satellite and the laser altimeter onboard should work more like a scanner, working with thin 'slices' of the earth's surface along the satellite's ground track, and then essentially exactly repeating its orbit on some later period. Thus, one would have instead of two waveforms per crossing to analyze, whole surface slices with waveforms overlapping and so would have enormous amounts of data available for analysis, and not only a patchwork of crossing points over some selected area.

Since the ICESat does have a repeated orbit, one might think 'why not use that?' Actually it can be used and might be very useful indeed, but since the ICESat has a repeat period of 33 days [4] and the operational periods are not much smaller and even less for some epoch (this depends on the epoch), there are not that many repeated tracks.

B. Cloud cover and comparing waveforms

From experience with the data and by comparing the 'missing points' to the cloud coverage one can say that there is a large correlation between missing points, but since thinner clouds also interfere with the laser pulses, these sources of error could perhaps be filtered out by combining a cloud cover database and the land cover classification algorithm.

ACKNOWLEDGEMENTS

REFERENCES

[1] Land cover topic centre, http://www.glcn-lccs.org/index.php?name=Content&pa=showpage&pid=1, last visit: September 2006.
[2] ICESat web page, *http://icesat.gsfc.nasa.gov*, last visit: September 2006
[3] CLC2000, 2006. Corine land cover 2000. *European Environment Agency,http://dataservice.eea.eu.int/dataservice/metadetails.asp?id=822*. last visit: September 2006.
[4] H.J. Zwally et al, Overview of the ICESat Mission, November 2005
[5] ICESAT web page, http://icesat.gsfc.nasa.gov, last visit: December 2006
[6] Wehr et al, Airborne laser scanning—an introduction and overview, Dec. 1998.
[7] Abshire et al., Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance, 2005
[8] National Snow and Ice Data Center(NSIDC) www.nsidc.orgc ; Zwally, H.J., R. Schutz, C. Bentley, J. Bufton, T. Herring, J. Minster, J. Spinhirne, and R. Thomas. 2003. *GLAS/ICESat L2 Antarctic and Greenland Ice Sheet Altimetry Data V001*. Boulder, CO: National Snow and Ice Data Center. Digital media.
[9] H. Duong et al, Full waveform analysis: ICESat laser data for land cover classification, April 2006
[10] IDL software distributor http://www.ittvis.com/
[11] ArcGIS software http://www.esri.com/
[12] http://www.mathworks.com/
[13] C. Shuman et al., Ice sheet elevations from ICESat: 2003–2005, submitted to Geophysical Research Letters, 2005
[14] Brenner et al, Derivation of range and range distributions from laser pulse waveform analysis for surface elevations, roughness, slope, and vegetation heights, September 2003.
[15] L'ARCHIVE SATMOS, http://www.satmos.meteo.fr/html/ARCHIVE.html/ .
[16] Rees "Physical principles of remote sensing" 2nd edition, 2001