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Digital terrain modelling for archaeological interpretation within forested areas using full-waveform laserscanning

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Abstract

The identification of sites within forested areas is one of the remaining unresolved issues for archaeological prospection. Airborne laser scanning can be a solution to this problem: due to the capability of penetrating forest to a certain degree (depending on the vegetation density) the determination of the terrain surface is even possible in wooded areas. To be able to identify archaeological structures, archaeologists have to interpret the resulting topographical data of a filtered ALS scan. This does not pose major problems with large structures. Smaller features, however, are much more difficult to identify, because their appearance in an ALS point cloud is very similar to natural and recent features, as for example dense brushwood, or piles of twigs or wood. Therefore, to eliminate potential sources of error, a high quality separation of terrain and off-terrain points is essential for archaeological interpretation while maintaining a high point density of the ALS data. Using conventional ALS systems, the possibilities to classify terrain and off-terrain points are limited and the results - especially in forested areas with dense understorey - are far from ideal for archaeological purposes. This paper will demonstrate how the new generation of full-waveform ALS systems can be used to get a much better classification of solid ground and vegetation cover and consequently DTMs, which can be interpreted archaeologically with much more confidence.

1. Introduction

Airborne Laser Scanning (ALS), also referred to as LIDAR (Light Detection and Ranging) [Ack99] [Kra04] [WL99] is an active remote sensing technique. It is used to produce dense and high precision measurements of the topography of the Earth's surface. The scanning device is typically mounted at the bottom or below an aeroplane or helicopter. For the determination of object points, the laserscanner emits short infrared pulses into different directions across the flight path towards the earth's surface and a photodiode records the backscattered echo and determines the distance to the reflecting object by the determination of the travel time.

Due to the capability of penetrating forest to a certain degree (depending on the vegetation density) the determination of the terrain surface is even possible in wooded areas [KP98] [PKK99]. However, in order to eliminate remaining off-terrain points from the derived last echo point cloud for the determination of the DTM advanced filter methods are necessary [SV03].

For archaeological interpretation purposes, a high quality separation of terrain and off-terrain points is essential. Using conventional ALS systems, the possibilities to classify terrain and off-terrain points are limited and the results - especially in forested areas with dense understorey - are far from ideal for archaeological purposes. This paper will demonstrate how the new generation of full-waveform ALS systems can be used to get a much better classification of solid ground and vegetation cover and consequently DTMs, which can be interpreted archaeologically with much more confidence.

2. Requirements of ALS for archaeological prospection

Though ALS has in the meanwhile found application in many areas, at present it finds only a very few archaeological applications related to archaeological prospection mainly in England and Germany [Bar03] [Bew03] [Cha06] [DACC05] [Hol01] [HHB02] [Mot01] [SR04] [Sit04].

With human occupation, the surface of the ground usually gets shaped (banks, ditches, mounds, etc.). When a site is abandoned, the structures will start collapsing. Without human interaction (especially agriculture), the process of decay can be stabilised by vegetation and the archaeological structures will form part of the ground's surface.

Because of its potential to determine a dense point cloud (up to several points per m^2) in high quality, archaeologists can investigate such sites, which are still surviving in relief even in forested areas. To be able to identify archaeological structures, archaeologists have to interpret the resulting topographical data of a filtered ALS scan. This does not pose major problems with large structures, like ruined castles, earthworks, tracks, or ridge and furrow. Smaller features, however, like round barrows, slag heaps, or kilns (to mention just a few) are much more difficult to identify. Their appearance in an ALS point cloud is very similar to natural and recent features, as for example dense brushwood, or piles of twigs or wood, which are - other than archaeological structures - actually off-terrain points.

Therefore, to eliminate potential sources of error, a high quality separation of terrain and off-terrain points is essential for archaeological interpretation while maintaining a high point density of the ALS data. Blunders and vegetation have to be filtered away, while the topography of buildings and any other man made structures (like ditches, banks, round barrows, walls etc.) should not be altered by the filtering techniques.

3. Problems of "Conventional" Data for Archaeological Interpretation

During the ALS point determination, the laser beam travels towards the earth's surface and illuminates different targets and all backscattering objects within the footprint area contribute to the received echo. The backscattering characteristics of the target depend on its size, distance, its reflectivity, and the directionality of scattering.

Flat surfaces in respect to the beam direction without vegetation reflect one short echo (approx. the same length as the emitted pulse), which the scanner receives as a delayed and attenuated signal. However, at spatially distributed targets, as it is typically the case in forested areas, only some of the laser energy is scattered back by the treetops, while the other energy penetrates through and is reflected by branches, bushes and the ground later on. In that way, a single laser beam can scatter back a complex echo waveform. Here, the returning signal is a superposition of echoes from the different scatterers. The echoes can be received as distinct signals if separated by distances larger than the range discrimination of the ALS system [WUD*06]. Within currently available commercial systems, this resolution is typically around 1.5 m [Kra04]. While this discrimination is high enough to clearly distinguish trees from the ground surface, it implicates that with those systems, it is difficult to distinguish narrow vegetation (as ferns, bushes etc.) from the terrain.

The elevation accuracy of ALS is composed of a systematic shift value (which mainly comes from the inaccuracies of GPS and INU measurements) and an unsystematic inaccuracy, which is mainly caused by the different range distribution within the footprint (e.g. vegetation cover of the ground [PKK99]). While the systematic shift value does not pose any problem for archaeological interpretation if the relative errors between two overlapping ALS strips are not too big, the unsystematic inaccuracies from the vegetation cover will result in topographic features representing for example single bushes, dense vegetation, or tree trunks. However, these off-terrain objects are sometimes difficult to discern from smaller archaeological features, as mentioned above.

Usually, for obtaining a DTM from a conventional scan, some of these topographical features can be sorted out by various filtering techniques. For archaeological purposes, however, filtering cannot be applied too rigid. Otherwise, smaller archaeological features are removed or smoothed, too. Therefore, while high vegetation and houses can be removed by filtering more or less reliably, low vegetation, like bushes and tree-trunks will still survive in the resulting DTM and will cause problems during interpretation.

4. Full-Waveform Sensors

The problems posed above mainly occur, because typical ALS sensors can only record up to a certain degree of distinct (typically 2 to 4) echoes from multiple targets touched by a single laser pulse using analogue detectors in real time during the acquisition process. As a result, these systems provide "only" an irregular 3D point cloud containing coordinates of the detected echoes.

However, the latest generation of commercially available ALS systems allow to discretisise the full-waveform of the received echo for each emitted laser beam. This discretisation allows us to gain further physical observations of the reflecting surface elements, which can be useful for a subsequent object classification. By modelling the full waveform as a series of Gaussian distribution functions, individual scatterers can be distinguished [HMB00] [WUD*06]. The results are estimates of the location and scattering properties of the individual targets: for each returning echo of a single laser pulse, the estimated coordinates of the scatterer, the echo width, and the amplitude is determined.

The echo width gives us information on the range distribution of all the small individual scatterers contributing to one echo, whereas the amplitude gives information about the radiometric scattering properties of the illuminated targets that contribute to one echo. If the echo width is small, a rather flat surface element was illuminated, whereas when it is large, scatters at different ranges contribute to the one determined echo (as it is the case with a tilted surface or a terrain surface with narrow vegetation (flowers, fern, small bushes)). In these cases, the estimated distance to the object

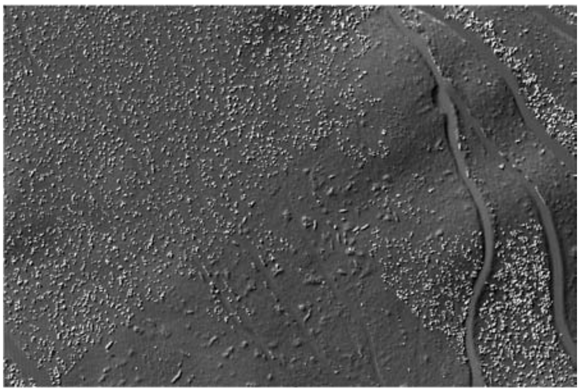

Figure 1: *DSM resulting from the unfiltered last echo point-cloud. There are many points, which represent, tree-trunks, very dense vegetation or narrow vegetation, which do not represent the actual ground.*

is a mixture of all distances to the individual targets. In the presence of low vegetation, the height of the estimated point will be too high and the point will not exactly represent the terrain surface.

The amplitude can give us additional information on the quality (intensity) of the reflection. It is, however, much more difficult to use the amplitude for classification purposes, because different effects as for example footprint area, the directionality of scattering, as well as size, topography, vertical distribution (number of backscatters from a single laser pulse), and reflectivity of the target contribute to a single amplitude. Therefore, it may not be as straightforward to use for classification purposes as reflectivity values recorded with passive imaging sensors [KK04].

Using amplitude and echo width, it is possible to investigate the return signal and extract additional ground characteristics. Consequently, much more information is available when classifying the point cloud into solid ground and vegetation cover.

5. Case Study

In April 2006, we launched the project "LiDAR-Supported Archaeological Prospection in Woodland", which is funded by the Austrian Science Fund (FWF P18674-G02). The goal of the project is to explore the potential of ALS for Archaeological Prospection in a densely forested area; specifically, to evaluate an approx. 190 km^2 forest area within the Leitha mountain range in an archaeological case study.

5.1. Test Data

During the pilot phase of the project, an ALS scan was conducted in the dormant period beginning of April 2006 using the latest generation of full-wave recording scanning systems. The purpose of this first flight was to get the optimal sensor configuration for scanning the whole area with its specific forest structure and canopy characteristics later on. The test area was carefully selected to represent different canopy density over already known archaeological features.

For the scans, we were using the RIEGL ALS-system LMS-Q560 operated by the company *Milan Flug GmbH*. The LMS-Q560 digitally samples and stores the entire echo waveform of the reflected laser pulses [HUG04]. Regarding the physical properties of ALS systems [Bal99], the LMS-Q560 has following specifications [WUM*04]: laser wavelength (1,5 μm), pulse duration (4 ns), pulse energy (8 μJ), pulserate (<100 kHz), beam width (0.5 mrad), scan angle (+/-22,5 deg), flying height (<1.500 m) and size (0.5 m @ 1 km) of the laser footprint on ground. Its multi-target range discrimination is 0,6 m.

The scan was performed on April 8, 2006. Flight altitude was about 600 m above ground, which resulted in a laser footprint size of 30 cm on ground. A total area of 9 km^2 was covered with a scan angle of +/-22,5 degrees by 26 parallel flight tracks, which had a width of approximately 500 m and an overlap of 50%. The real scan rate was 66 kHz that resulted in an overall mean point density of eight measurements per m^2. The GPS operated with a frequency of 1Hz, whereas the inertial measurement unit (IMU) recorded the attitude with 250Hz. While scanning, the total area was additionally covered vertically using the integrated DigiCAM H/22 system with a resolution of 22 megapixels.

5.2. Full-Waveform Processing and Filtering

In the first step a Gaussian decomposition of the full-waveform data was performed [WUD*06]. Based on this procedure the 3d co-ordinates of all detected echoes are determined and stored together with the additional information (amplitude, echo width) determined from the fitted Gaussians. From this dataset, we selected the last echoes together with the additional information for the further processing.

To eliminate remaining off-terrain points from the derived last echo point cloud (Figure 1), we used the theory of robust interpolation (RI) [KP98] within a hierarchic framework [BPD02], which is implemented into the software package SCOP++ [KO05]. The most important feature within this coarse to fine approach is the method of RI. RI integrates the elimination of off-terrain points and the interpolation of the terrain surface within the same process. The two most important entities of the RI are a functional model and a weight model. The functional model has to allow the approximation of the terrain surface with the consideration of individual weights for each irregularly distributed point. The weight model has to assign an individual weight to each point.

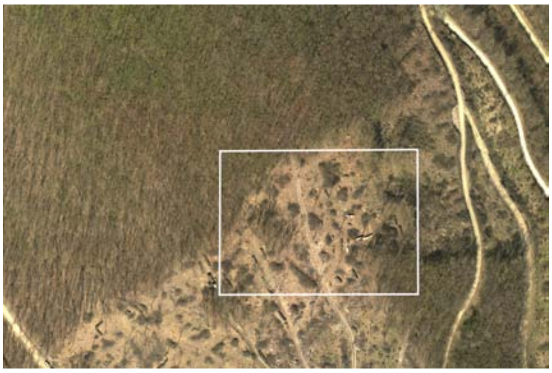

Figure 2: *Vertical aerial photograph of study area 1 taken during the scanning procedure. The white rectangle marks the outline of Figure 6.*

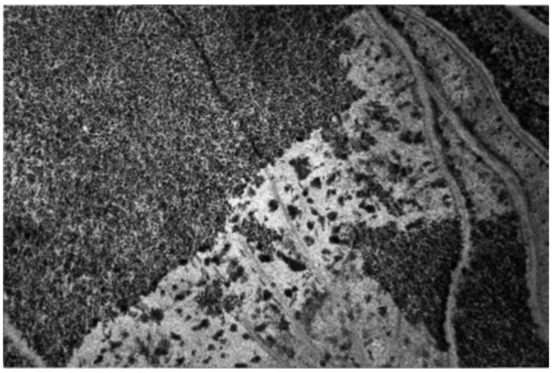

Figure 3: *Intensity image of study area 1. Bright pixels represent a high percentage of the original laser energy returned as last-pulse echo.*

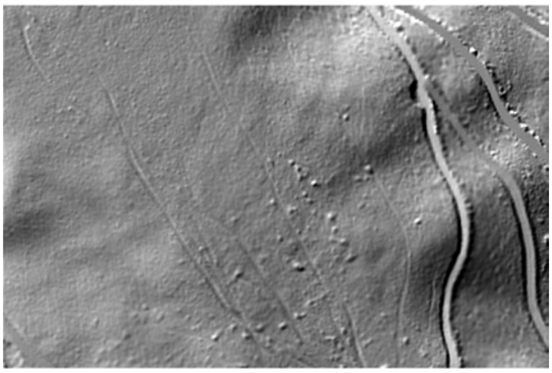

Figure 4: *DTM of study area 1 after Gaussian decomposition and filtering using robust interpolation with an eccentric and unsymmetrical weight function within a hierarchic framework.*

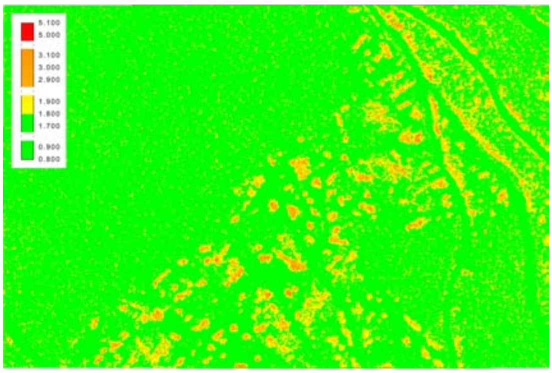

Figure 5: *Mapped echo widths of study area 1. While in the wood, high values (yellow to red) occur only occasionally, bushes and clearance piles show high values throughout.*

Figure 6: *Zoomed view of 3D point cloud and orthophotograph after application of the threshold value. Most clearance and even wood piles are filtered out and are not represented in the point data any more.*

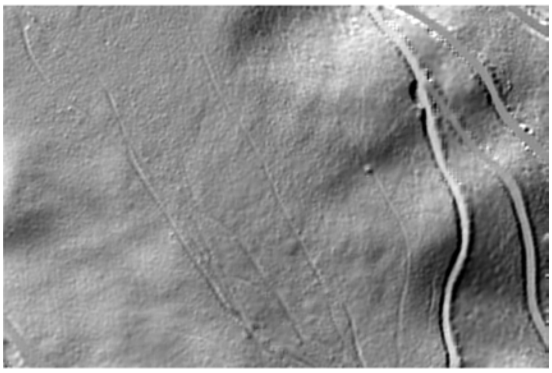

Figure 7: *Resulting shaded DTM after removal of points with a high echo width and hierarchic robust interpolation.*

For the elimination of off-terrain points from ALS data, an eccentric and unsymmetrical weight function is typically in use [BPD02]. This weight function assigns iteratively a low weight to points that are significantly above the terrain (e.g. on the vegetation) whereas terrain points are assigned a high weight. The RI is applied within each data pyramid level of the hierarchic setup. For the stepwise refinement, a tolerance band defined in respect to the resulting coarse surface model is used. This step-by-step process leads to a final surface model that allows to separate terrain from off-terrain points using a threshold value (typically plus and minus three times sigma of the height accuracy of the input points). The whole process of filtering is also demonstrated at the EuroSDR Distance Learning Course "Filtering and Classification of Laser Scanner Data", available under http://www.ipf.tuwien.ac.at/eurosdr/index.htm.

In an archaeological dataset, vegetation should be filtered out, but walls, banks, ditches, and smaller archaeological structures should be kept within the resulting DTM. One therefore has to be very careful with the tuning of the parameters of the iterative filtering steps within the hierarchic filter strategy. Due to the fact that no big buildings were present within our test area, we started the procedure with two data pyramid levels and did not use the additionally available pre-elimination of large building regions. For the first level, a point density of 1 point/m^2 was chosen. After the thin out of the original point cloud (approx. 8 points/m^2), we performed the RI using an asymmetric weight function in order to eliminate the off-terrain points within this data pyramid level. This was followed by the refinement step with the help of a tolerance band in respect to the 1 m-terrain model that discarded all last echo points 0.5 m above the terrain surface. Finally, we applied the RI to the remaining data of the finest level.

This procedure was applied on one hand to all last echo points without considering the additional information provided by the full-waveform processing, whereas on the other hand the same process was applied to a subset of the points after a simple pre-elimination step of all last echo points with a large echo width. To demonstrate the potential of this way of point classification and the improvement achieved with the consideration of the additional point attributes gathered by the full-waveform analysis, two small areas from the test-scan will be presented in the following.

5.3. Study Area 1

The first area does not contain archaeological structures. The vertical photograph (Figure 2) shows that the upper area is covered with deciduous wood, while in the lower area, the wood is being cleared. Apart from a few groups of trees, the lower area is covered with clearance piles of twigs and logs from the felled trees. On the right side, there is a bundle of roads, where dense bushes accompany the individual roads.

The situation is well reflected in the intensity image (Figure 3), which is derived from the amplitude values, which we got from Gaussian decomposition of the full-waveform data. The bright pixels show that a high percentage of the original laser energy returned as last-pulse echo. The darker the pixels get, the less energy returned to the sensor from the ground. Deciduous forest and small groups of trees consist of a mixture of high and low amplitude values, while the reflections coming from the cleared soil have high amplitudes. Clearance piles show equal areas of low amplitude values.

After Gaussian decomposition and filtering, the resulting shaded DTM shows that the procedure worked quite well in the wooded area (Figure 4). In the cleared area, the DTM shows still many small features with a diameter of 5 - 6 m and a height of 0,2 - 1 m. Without further information, it would be hard to interpret and decide about their potential archaeological meaning. Additionally, the dense bushes next to the roads are still present.

If we map the individual echo widths (Figure 5), we clearly can identify the piles of twigs and logs, which had low amplitude values as having also large echo widths. Analysing the mapped echo widths and their histogram, we defined a threshold value (in this case 1,7 m) and consequently removed all points from the original data set with higher values (Figure 6).

The resulting DTM shows a much better surface representation with almost all of the vegetation and clearance piles removed (Figure 7). This result is now much easier to interpret with a minimized risk of identifying low, dense vegetation as potential archaeological feature.

5.4. Study Area 2

In the other study area, we wanted to test, whether the procedure of eliminating points with higher pulse-width would affect archaeological features. Therefore, we analysed a small area within the Iron Age hillfort of Purbach. The area under investigation shows parts of the ramparts and a graveyard consisting of at about 50 round barrows (Figure 8).

The massive ramparts are clearly visible despite the vegetation in the aerial photograph (Figure 8). The round barrows, however, vanish under the dense vegetation cover. The intensity image (Figure 9) let us distinguish three different kinds of vegetation covering the barrows: bushes (1), trees without brushwood (2), and trees with brushwood (3).

After elimination of all echoes with a high echo width (threshold value: 1.7 m) (Figure 10), the comparison between the two DTMs (with and without pre-eliminated points) clearly shows, that the archaeological features were not affected by the procedure (Figure10 and Figure 11). The difference map reveals that the measurements of only a few barrows had been affected by low vegetation, which was removed consequently (Figure 12).

Figure 8: *Vertical aerial photograph of study area 2. While the massive ramparts are clearly visible, the round barrows (1) vanish under the dense vegetation cover.*

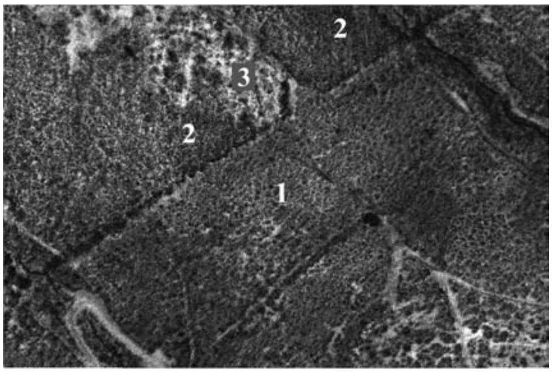

Figure 9: *Intensity image of study area 2; the amplitude values let us distinguish three different kinds of vegetation: bushes (1), trees with brushwood (2), and trees without brushwood (3).*

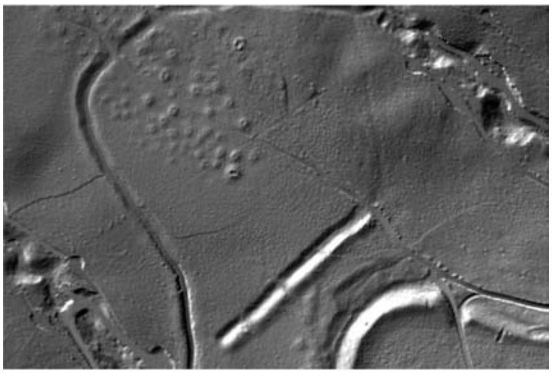

Figure 10: *Resulting shaded DTM after hierarchic robust interpolation.*

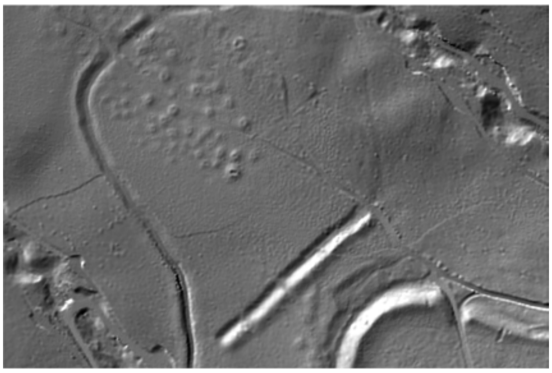

Figure 11: *Resulting shaded DTM after removal of points with a high echo width and hierarchic robust interpolation.*

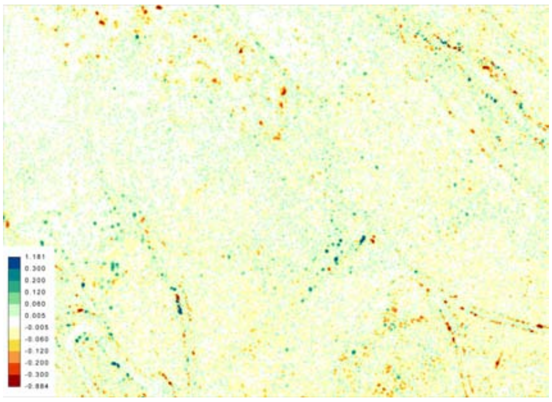

Figure 12: *Z-coded difference between DTM1 and DTM2 (with and without eliminated points).*

6. Conclusion

The paper demonstrated the potential of full-waveform analysis. With a full-waveform recording, a lot of more information about the received laser echo, like the detailed distribution of targets in the beam path, their reflectance and their vertical extent is stored.

In that way, it is possible to investigate the return signal and therefore further point characteristics can be determined. Based on this information, we can now classify the ALS points with much more confidence into solid ground and vegetation cover. This has an important impact (not only) on archaeological interpretation: in archaeological terms, we now have means to identify features in the point-cloud, which are remains of bushes or other low vegetation that was not completely penetrated by the laser pulse. After eliminating these points, we get a more reliable DTM, where most local topographic features are in fact local topographic elevations of the ground surface.

Within the paper, the usage of a simple threshold operation in order to pre-exclude points situated within low vegetation structures is demonstrated. However, this simple threshold procedure can be problematic in steep terrain, where the illuminated tilted terrain surface within the footprint can increase the echo width. Therefore, we will extend our procedure for steep terrain in the future. Furthermore, we will consider a calibration of the sensor system in order to determine a system independent interpretation of the received amplitude values [WUD*06]. This calibration procedure should allow to convert the received echo amplitude into the radar backscatter cross section which provides a system independent information about the radiometric surface reflection properties.

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