FLI-MAP data possibilities for forest inventory

At the request of: Data ICT Dienst of Rijkswaterstaat, the Netherlands
Project leader: Andries Knotters

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1. Introduction

This research documentation is organized in 5 major parts. In Chapter 1 the question is divided into several sub questions which we answer within the report. Furthermore, a research plan is given. Chapter 2 contains a literature review of the topic tree measurement with airborne data and finally concludes the new possibility with the high density airborne system FLI-MAP 400. In Chapter 3 the algorithms investigated to fulfill the conclusions of the literature study are roughly explained and their possibilities are stated. Chapter 4 is evaluating the results of the expected possibilities. And finally conclusions are drawn from the results and the main question is answered in Chapter 5.

1.1 Research question

The Data ICT Dienst of Rijkswaterstaat asked the section Optical Laser and Remote Sensing (OLRS) at TU Delft to investigate the potential of FLI-MAP 400 data to automatically measure forest inventory
parameters of single standing trees. This focuses directly on the stem diameter. After an extensive
literature study we could ask the following sub questions:

1. Is it possible to delineate the trees?
2. Is it possible to pre filter the tree data?
3. Is the higher point density sufficient to segment the stem from delineated trees?
4. Is it possible to measure the diameter automatically in the extracted stem?
5. Are there enough points on the stem to measure the diameter?
6. Which methods are suitable to extract the diameter?
7. Which precision is to be expected in an automatic measurement system?
8. Are there existing solutions to extract the stem diameter from the data?
1.2 Research planning

The research contained 3 Phases, which are described here:

**Phase 1:**

- 3 days of literature study
- 3 days of evaluating existing software (Terra Solid and Cyclone)
- 1 day of field work
- 2 day of data organization
- 5 days of writing the literature study and the conclusions

14 days

**Phase 2:**

- 2 days for delineation of random and hand measured trees from the field work with a region growing algorithm
- 3 days of filtering the trees from the under grown vegetation
- 4 days of adjusting and extension of the existing scene description algorithm for terrestrial data to the FLI-MAP 400 data.

9 days

**Phase 3:**

- 5 days for investigating and implementing the automatic measurement of the stems

The whole project contains: 14 + 9 + 5 = 28 days
2. Literature Study

The literature study contains 4 parts. First, a short comparison between classical LiDAR systems and the new FLI-MAP system is given. Second, an overview over forest inventory methods and the extractable parameters are investigated. An example of a stem diameter measurement system and the conclusions from this study finalizes this chapter.

2.1 FLI-MAP System

The new FLI-MAP 400 System is an airborne LiDAR system that is able to obtain approx. 50 height points per square meter at 100m height and 20 m/s. The main difference to traditional airborne LiDAR is that it is placed on a helicopter instead of an airplane. The resulting differences are:

- Operated at very low altitudes (50–150 meters)
- 4 integrated photo and video cameras
- Double laser system to eliminate shadowing.

The 2 lasers in the system are reflectorless rangefinders firing 150,000 laser pulses per second in a 60-degree angle perpendicular to the flight path. With both lasers scanning, the reflected laser intensity of the terrain and objects also gives information on the type of surveyed material. In the Netherlands airborne laser altimetry has recently been used for the production of a detailed elevation model of the whole country. The project known as AHN (Actual Height model of The Netherlands), is meant to have available detailed information about elevation, highly demanded by water boards, provinces and the national government. Comparing the AHN systems with the FLI-MAP system and the new FLI-MAP 400 system results in the figures as displayed in Table 1 below.

<table>
<thead>
<tr>
<th></th>
<th>FLI-MAP</th>
<th>FLI-MAP 400</th>
<th>AHN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aircraft height</strong></td>
<td>50–150m</td>
<td>50–400m</td>
<td>1000m</td>
</tr>
<tr>
<td><strong>Aircraft speed</strong></td>
<td>50–80 km/h</td>
<td>50–80 km/h</td>
<td>250 km/h</td>
</tr>
<tr>
<td><strong># Points/m²</strong></td>
<td>10–25</td>
<td>~50</td>
<td>1</td>
</tr>
<tr>
<td><strong>Systematic Error X,Y</strong></td>
<td>8cm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Standard Deviation X,Y</strong></td>
<td>5cm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Systematic Error Z</strong></td>
<td>5cm</td>
<td>-</td>
<td>5–15 cm</td>
</tr>
<tr>
<td><strong>Standard Deviation Z</strong></td>
<td>5cm</td>
<td>-</td>
<td>15 cm</td>
</tr>
</tbody>
</table>
2.2 Airborne forest inventory methods

This literature study focuses on a general overview of LiDAR possibilities for forest inventory. An in-depth study about single tree measurement was made apart from this study. The FLI-MAP 400 system delivers a high point density (around 50 3D-points per square meter) with a small footprint. The general trade off between small and large footprints is shown in Table 2 and was found in (Behera and Roy, 2002). But it focuses on data with 6 to 10 measurements per square meter for small footprint data. Therefore the last conclusion has to be reevaluated for the FLI-MAP system. A hint to this is found in (Andersen, et al., 2006), which demonstrated that small beam sizes are far more

Table 2: Benefit and drawbacks of small and large footprints compared.

<table>
<thead>
<tr>
<th>Small footprint lidar</th>
<th>Large footprint lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small diameter beams frequently miss the tree tops.</td>
<td>Large footprint beams avoid missing the tree tops frequently. By increasing the footprint size to the approximate crown diameter of a canopy-forming tree (~ 10-25 m), laser energy consistently reaches the ground, even in dense forests.</td>
</tr>
<tr>
<td>Because of their small beam size and low flying height, mapping large areas requires extensive flying, thus adding to the budget.</td>
<td>Large footprint systems fly at higher altitudes and enable a wide image swath, which reduces the expense of mapping large areas on the ground.</td>
</tr>
<tr>
<td>Usually, small footprint systems record the first and/or last returns, thus making it difficult to determine if a particular shot has penetrated the canopy all the way to the ground.</td>
<td>Large footprint systems digitize the entire return signal, thus providing data on the vertical distribution of intercepted surfaces from the top of the canopy to the ground.</td>
</tr>
<tr>
<td>In areas of high canopy only one in several thousands returns may be from the ground, thus giving rise to the risk of inaccurate height measurement relative to the ground.</td>
<td>This risk is reduced in case of large footprint lidars.</td>
</tr>
<tr>
<td>It may not be optimal for mapping forest structures.</td>
<td>This has many advantages for mapping of forest structures. But the risk is that bases from the blurring of ground and canopy can become large as well, again affecting height recovery.</td>
</tr>
</tbody>
</table>

accurate to measure single trees.

The literature states clearly the main tasks for working with LiDAR data:


The best automated result for tree delineation was given in (Tiede, et al., 2005), which achieves a 72% correct delineation of all trees in the given forest sample. The proposed watershed algorithm (Koetz, et al., 2006) shows species depended correctness between 60% and 90%. Most often no method was mentioned or an interactive, manual approach for tree delineation was used to determine
the single trees (Holmgren, 2004, Opitz and Blundell, 2006, Tickle, et al., 2001). The combination of airborne photos with LiDAR data to identify tree crowns is reported in (Popescu, et al., 2003) and gives 97% correct tree detection. But no information about the level of automation is given. In (Tiede, et al., 2005) an average detection rate of around 45% was given for automated tree detection systems. Furthermore, the investigation of automated extraction methods (Diedershagen, et al., 2003) came to the conclusion that trees can be identified by only looking at the height data. A comparison between an image supported approach using the FORGIS system and a height based algorithm on LiDAR data has demonstrated this.

Except for one publication (Lim, et al., 2001) the problem of under estimation of tree heights up to 3.6 meters (Clark, et al., 2004, Ni-Meister, 2005, Roberts, et al., 2005) from LiDAR data was reported, for both large and small footprints. In (Lim, et al., 2001) this under estimation did not occur, but only 146 out of 600 trees were considered. In (Ni-Meister, 2005) it was further documented that LiDAR measurement is very sensible to tree density, but less sensible to tree heights. The same under estimation problem of around 20% of the actual size is reported for crown sizes in (Roberts, et al., 2005). For both, tree height and crown size, a dependency on the measured species is outlined though out the publications (Tomoaki, et al., 2005).

None of the publications estimated the diameter at breast height, as requested by Rijkswaterstaat. Only hints are found in (Buddenbaum and Seeling, 2007, Diedershagen, et al., 2003, Diedershagen Oliver, et al., 2003). Therefore, most publications try to estimate the biomass volume from tree height and crown size and the known species (Buddenbaum and Seeling, 2007, Holmgren, 2004). It is only stated in (Diedershagen, et al., 2003, Diedershagen Oliver, et al., 2003) that the diameter at breast height can be extracted. But no evaluation is done on that. The breast height diameter can be estimated via tree height, crown size and the species. This is an erroneous estimation, like stated before. A detailed example of such an estimation is given system is given in the next subchapter.

For many applications it is not necessary to compute a single tree height. Therefore the creation of a Digital Canopy Map is preferred in (Andersen, et al., 2005, Hill and Thomson, 2005, Popescu, et al., 2003). This approach is used for getting an average tree height and for creating maps e.g. for fire departments. An overview of extractable parameters and the corresponding methods is listed in Tab.2.

### 2.3 Example of a Single Tree measuring system

The Single Tree Remote Sensing (STRS) system is a semi-automatic system and uses information of allometry. Allometry is for instance the information on the relative size of the plant parts and this information is species dependent. In this study, the estimation of stem diameter was based on tree species, height and crown width. In addition, allometry information varies within tree species as trees adapt to the intra and inter-specific competition and site conditions. The allometry information had also been used together with LiDAR data for crown delineation. The system measures the following variables;
1. Photogrammetric 3D treetops position using multi-scale template matching,
2. Photogrammetric tree height using the 3D tree top position and DTM,
3. LiDAR based tree height,
4. Tree species through manual interpretation,
5. Crown width using both image (multi-scale template matching) and LiDAR (least square adjustment of a crown model with LiDAR point clouds),
The crown modeling using LiDAR was based on the following model:

\[ r(h_r) = a_1 \sin(h_r) + a_2 \quad (1.1) \]

Where,
- \( r(h_r) \) – crown radius at a relative height
- \( a_1 \) – relationship between tree height and maximum crown radius
- \( a_2 \) – shape parameter
- \( a_3 \) – if this value deviates from zero, the canopy might have plateau shape

LiDAR data is used to derive parameter \( h_r \) and at the same time value for \( r(h_r) \) can be calculated. Thus the \( r(h_r) \) value can be used to solve this equation by means of least square adjustment. The allometric approach for stem diameter estimation is defined in equation 1.2.

\[ \sqrt{d_{1.3}} = a_1 \sqrt{h} + b_1 + d_{2cm}^2 + e \quad (1.2) \]

Where,
- \( d_{1.3} \) – stem diameter at 1.3 m height from tree height \( h \) (the \( h \) value is derived from 3D treetops positioning method)
- \( d_{2cm} \) – Maximum crown width for species \( t \) (obtained from LiDAR and Aerial Photo)

The drawbacks of this approach are:
1. The combination of LiDAR and Aerial Photo might increase operational cost and requires almost simultaneous data to minimize discrepancies between data,
2. the model for tree variable derivation is species dependent and heavily relies on good information of specific area, on the other hand, it was also noted that tree variables within species also varies due to the intra and inter-specific competition and site conditions,
3. Visual inspection for tree species classification is time consuming and automatic classification of tree species from aerial photo is quite difficult due to low spectral resolution of this data.

### Table 3: Extractable forestry parameters and their methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Description on method</th>
<th>Forest properties</th>
<th>Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy profile area</td>
<td>The canopy profile area is directly related to the logarithm of the timber volume</td>
<td>Volume of timber</td>
<td>(Maclean and Krabill, 1986, Maclean and Martin, 1984)</td>
</tr>
<tr>
<td>Metric</td>
<td>Description</td>
<td>Predictors in regressions models for estimation of mean tree height, basal area and volume</td>
<td>Reference</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Canopy reflection sum, ground reflection sum and Canopy closure</td>
<td>Canopy reflection sum is the sum of the portion of the waveform return reflected from the canopy. Ground reflection sum is the sum of waveform return reflected from the ground multiplied by a factor correcting the canopy attenuation. Canopy closure was approximated by dividing the sum of the canopy and ground reflection sums.</td>
<td>(Means, et al., 1999)</td>
<td></td>
</tr>
<tr>
<td>Canopy height and density metrics</td>
<td>Canopy height metrics included e.g. quantiles corresponding to the 0,10,...,90 percentiles of the first pulse laser canopy heights and corresponding statistics, where as canopy density corresponded to the proportions of both first and last pulse laser hits above the 0,10,...,90 quantiles to total number of pulses.</td>
<td>Canopy height and density metrics</td>
<td>(Naesset, 2002)</td>
</tr>
<tr>
<td>Tree cover and Surface cover</td>
<td>Tree cover was calculated from the proportion of laser hits from tree canopy divided by the total number of laser hits. Surface cover was defined as the proportion of laser hits from the surface and the total number of hits.</td>
<td>Area of the tree and area of the ground surface</td>
<td>(Riano, et al., 2003)</td>
</tr>
<tr>
<td>Relative standard deviation of tree heights, the proportion of single returns and the proportion of first return, proportion vegetation points, mean intensity, standard deviation of both single and surface returns</td>
<td>Number of returns that were located above the crown base height divided by the total number of returns from the segment. This information is used for tree species classification.</td>
<td>Tree species classification</td>
<td>(Holmgren and Persson, 2004)</td>
</tr>
<tr>
<td>Crown shape</td>
<td>Crown shape is defined by fitting a parabolic surface to the laser point cloud.</td>
<td>Crown shape</td>
<td>(Holmgren and Persson, 2004)</td>
</tr>
</tbody>
</table>
2.4 Conclusions

None of the statistical analysis done on LiDAR data gives sufficient results. Moreover it is stated in publications, that a 100% result will never be achieved with these methods (Diedershagen, et al., 2003, Diedershagen Oliver, et al., 2003). It is even suggested to combine field measurements with LiDAR measurements to obtain reliable data for forest inventory (Andersen, et al., 2006). It has to be mentioned here that none of the publications is validated against an extensive field measurements. For example in (Ni-Meister, 2005) no reliable results where given about the crown size. Further the estimation of derivable forest parameters was often not carried out, because of the inaccuracies in the crown size and tree height estimations. Only one system was found that tries to estimate the stem diameter, but none of the investigated publications used this estimation technique. None of the publications took a geometry based method into account, which will be investigated regarding the very dense FLI-MAP data.
3. Algorithms

This chapter describes the investigated possible automatic solutions for each sub problem. The named sub problems are the delineation of the trees in 3.1, the new pre-filtering algorithm in 3.2, the newly developed Skeletonization to extract the geometry of the stem from point cloud (3.3 Second) and finally a newly developed analyzing method for stem diameters in high density airborne data. At this stage we give simple examples of the principle on real data. An evaluated test set is then shown in the Chapter 4.

3.1 Tree delineation

Individual trees were extracted by using the following processing steps:

1. Tree top detection. This process was based on the local maximum filtering that considers the maximum and minimum size of the tree crown. Further processing takes place to refine the location of the final tree tops based on their distance to one another.

2. The final tree top locations were then used as starting points for region growing segmentation. The segmentation was based on the inversed version of watershed segmentation.

3. The final regions of individual trees may include point clouds that belong to undergrowth vegetation and the crown of the adjacent trees. Therefore, further processing is needed to filter out this noise before the tree variable extraction process.

3.2 Pre-filtering of the data

A specialized filtering algorithm was developed during this research to filter the undergrowth vegetation. The characteristics of the FLI-MAP data allow the use of a distance histogram of the tree to the center line for filtering the data. This histogram strongly reflects the geometry of a tree. The tree filtering process relies on the fact that a tree would have distinct parts in the histogram that represent the crown, trunk, and ground with or without undergrowth vegetation. The tree is assumed to have high frequency of laser pulses from the crown and undergrowth vegetation, while fewer from the trunk. The filtering process starts from the top of the tree and the shape of the histogram was used to identify points that belong to the tree crown and the trunk. Nearest Neighbor (NN) segmentation is then used to classify the point cloud into tree crown and trunk. The search for the tree trunk continues by iterative analysis of the shape of the histogram at certain heights above the ground. This process is coupled with the NN segmentation to add some more points to the tree trunk. The search continues until the process is no longer able to distinguish between tree trunk and the undergrowth vegetation. If the process stops before it reaches the ground surface, the remaining points that belong to the tree trunk were identified by fitting a 3D line and the NN segmentation takes
place based on the distance from the line. Good results were achieved for trees at the border of the forest and single trees. Figure 1 shows a filtered tree in the middle illustration.

![Figure 1: Left, a delineated tree from the data, in the middle a tree after the filtering and on the right the computed skeleton.](image)

### 3.3 Skeletonization of the trees

The basis for this algorithm is described in detail in (Bucksch and Lindenbergh, 2007). It uses the analysis of the 6 directions in which the point cloud is intersecting the octree cells, to generate an initial octree-graph with the direction as a label on every edge. This graph is then further reduced to the skeleton. Compared to the method described in the paper (Bucksch and Lindenbergh, 2007), a faster method was developed. Instead of removing cycles from the graph, we generate an initial triangle situation, and retract the octree graph until the skeleton remains. The retraction is based of merging two vertices in the octree graph that are connected with the same direction via one vertex in this triangle. This will result in another triangle in the graph which is treated the same way, until the skeleton remains.

An "easy" test tree (Figure 1) with a clearly defined stem was chosen to implement the modifications in the scene description/skeleton. This algorithm was modified and adapted to the characteristics of
airborne data. These changes within the volume descriptor of the octree lead to clear results in the stem area.

The extracted skeleton shows that it is possible to get a sufficiently accurate segmentation of the stem on filtered data, which covers the breast height (green line in Figure 1 right). This satisfies the requirements for this study; in addition the tests have shown that further research can lead to the identification of single branches (Figure 1 right). Also the crown size may be extractable, but the detailed crown geometry will still be not described. The properties of the extracted description allow the conclusion that the diameter is extractable. We found several surface maxima/minima in the skeleton which can significantly be separated from the centerline parts of the skeleton. These maxima represent the radius (visible as small pink streaks to the left and right along the stem). In comparison to other previously investigated centerline/skeleton methods the extracted graph always contains the center line, whereas changes on the surface (e.g. by noise) do not influence the extracted center line; they just result in different maxima/minima (Figure 1 right pink streaks). This behavior makes the method extremely robust for the target application (Figure 3).
Figure 2: Test tree to calculate the Skeleton on the test data, measured in Cyclone 5.7
Figure 3: Skeleton of the tree in Fig.3. The stem is clearly represented by a line centered in the point cloud.
3.4 Measurement of the stem diameter

For measuring the diameter at breast height we investigated 2 methods:

1. Fitting a cylinder to the extracted stem data, which is the traditional least squares fitting used in standard software like cyclone (Lukács, et al., 1998)
2. Analysis of the histogram of distances of the stem points at breast height to the extracted skeleton, which is a newly developed method making use of the extracted skeleton.

While the last square fitting is already exhaustively documented in literature e.g. (Lukács, et al., 1998), the explanation of the new histogram analysis is given within this report. The method chooses the first significant peak from the back of the histogram of distances of the stem points at breast height to the extracted skeleton. If two similar strong peaks are beside each other (we chose a threshold of 1 point), they are combined into one. The result is the average of all points belonging to this peak. We ignored measurements giving us distances to the skeleton smaller 15 cm. Further we ignored the 10% largest distances to the skeleton. The peak distance is assumed to be the radius of the stem. The diameter of the stem is twice this radius.
3.5 The suggested process for stem diameter extraction

- Input Data
  - Single Trees
    - Tree Filtering
      - Filtered Trees
        - Skeletonization
          - Skeleton Graphs
            - Stem extraction and diameter measurement
              - Diameter per stem
4. Results

We have chosen a test set of 8 trees to estimate the diameter at breast height (Figure 4, Figure 5). These trees we delineated, filtered, skeletonized and measured. During the development of these algorithms we used additional randomly extracted trees to test the robustness of our implementation. We show in this chapter the results of the 8 trees and add the random examples when they where used. Our test set groups in two times 4 trees:

- Single standing trees
- Trees on the forest border to simulate incomplete data sets.

4.1 Tree delineation

The 8 delineated are 4 single trees with different crown sizes and 4 trees on the forest border. In all of the unfiltered tree data sets the stem is visible (Figure 4). Trees within the forest are hard to extract. We used GPS positions to find the trees in the data. The stem is visible in all cut outs (Figure 4, Figure 5). It has to be mentioned that the tree in the left upper corner of Figure 4 consists of several stems. Here is definitely a limit of the technology. Several stems under a huge crown won’t be extractable, but an overall diameter around all stems may be extractable.

As shown in Figure 4 and Figure 5 we first kept the ground in these data sets. For automatic stem extraction it will be necessary to deal with the ground. The ground leads to huge graphs in the scene description/skeleton. Therefore it was necessary to test if this can be handled on a standard Personal Computer. The solution was to operate internally only on one Graph-Dataset, while all intermediate Graphs during the calculation just know about there adjacency List. This allows copying of the scene description without wasting too much memory. But it can be foreseen that a platform with sufficient memory handling (like a database environment) has to be used. Furthermore, it is suggested that the ground will be removed by a prefiltering beforehand, to reduce calculation overhead.
Figure 4: 4 unfiltered, delineated, single standing trees. The stems are visible, even at the tree in the left upper corner. But the tree in the upper left corner has several stems.
Figure 5: 4 delineated, unfiltered trees on the forest border to simulate incomplete data sets
4.2 Pre-filtering of the data

The test on the pre-filtering where already done before it was possible to visit the test area. Therefore we used different trees to test this algorithm. All our 4 test cases where successful, as shown in Figure 6, Figure 7, Figure 9 and Figure 8.

Figure 6: Tree with under grown vegetation and vegetation along the stem which stays unfiltered

Figure 7: Tree with bottom vegetation on the ground after successful filtering
Figure 8: A test set to evaluate if the case of no under grown vegetation is handled correctly.

Figure 9: tree with under grown vegetation and low branches. The branches are kept in the data set.
4.3 Skeletonization

A common test setup was chosen to calculate the skeleton of the trees. These settings do not guarantee a good result for all cases, but most standard cases can be resolved with these settings. Setting adjustments for extreme cases are mentioned throughout the text. To prove the robustness of this method we used the unfiltered trees with removed ground.

**The test setting:**

All trees where skeletonized with the algorithm input parameters

- 1m minimum voxel size
- 40% voxel threshold to force almost regular space division

These parameters are related to the ones used for octree subdivision in (Buddenbaum and Seeling, 2007):

In this test setting we experienced calculation times between 30 seconds and 5 Minutes per tree, depending on the structural complexity of the tree. It has to be mentioned that the used algorithm is still under development and still has optimization potential.

We selected 8 random trees of different sizes from the data set to widen our test data set for the algorithm. These trees cover the major geometric tree form in the test area. From all these randomly selected trees the skeleton graph was fully automatically extracted. This can be seen in Figure 10.

Furthermore we extracted the skeleton for the entire set of validation trees excluding the ones within the forest. We still include trees on the forest border, to simulate the case, that a tree is only partly scanned. We will use the skeleton to “navigate” though the tree, up to the breast height and extract and appropriate subset of the point cloud to measure the diameter. We described these trees in detail in the caption of the corresponding picture. Figure 11, Figure 12 and Figure 13 show trees standing in a row.

A remarkable case is shown in Figure 17. Changing the input parameters may resolve this case, but will definitely result in extremely high calculation times. As a result we could show, that in the huge majority of the cases could be resolved and that there are foreseen solutions for the unsolved example in Figure 17.
Randomly selected trees and their corresponding skeleton:

Figure 10: 8 randomly selected trees to test the skeletonization algorithm
8 hand measured trees from the test set:

Figure 11: hand measured diameter 0.79m. The skeleton of the stem is still valid. Noise around the stem only leads to outwards pointing skeleton parts.

Figure 12: hand measured diameter 0.55m. The same effects are visible then in the picture above.
Figure 13: hand measured diameter 0.64m. The skeleton stays connected even in parts with very low point density.

Figure 14: hand measured diameter 0.55m. A tree partly scanned. The stem skeleton is still extracted, but contains a loop which my result in less accurate diameter measures. This can be avoided by using higher minimum voxel sizes, but will increase the computing time.
Figure 15: hand measured diameter 0.54m. Another partly measured tree with a clearly defined stem.

Figure 16: hand measured diameter 0.51m. A tree partly scanned with its extracted stem. Noise leads in this case to the same "streaks" like explained above.
Figure 17: hand measured diameter 3.48m (around all the stems). This figure shows the unsolved case with the given input parameters. These trees consist out of several stems which could not be resolved with the chosen resolution. Further investigations to these cases should be done.

Even on the unfiltered data the stem was identifiable (Fig.4) in the scene description graph. To select the longest sub graph, which is connected to the ground, in such a scene description, will lead to an automatic stem extraction. Until now the skeleton for one tree with removed ground was calculated. This tree is shown in Fig. 3. It has an approximated crown diameter of 15m and an approximated height of 15m. The removal of the ground reduced the calculation time to one forth, further prefiltering for the crown can speed up the process again. The results for trees within the forest have to be investigated. In the following weeks the skeletons for all the trees will be calculated, to see what happens on the highly structured scans (which need far more computation time because of the fine details in the structure) on the forest border.
4.4. Measurement of the stem diameter

4.4.1 The test results

Tree 1

Extracted distances to the skeleton:

0.318378, 0.337601, 0.318599, 0.466131, 0.437892, 0.524484, 0.496489, 0.184393,
0.215356, 0.203302, 0.254552, 0.197776, 0.320315, 0.183783, 0.236644,
0.227383, 0.169753, 0.226196, 0.274489, 0.190139, 0.203144, 0.555008,
0.329434, 0.442175, 0.341066, 0.502474, 0.382245, 0.426962, 0.304445,
0.179982, 0.222764, 0.264305, 0.206834, 0.169508, 0.187589, 0.36842, 0.358254

<table>
<thead>
<tr>
<th>Manual diameter</th>
<th>Fitted Cylinder</th>
<th>Histogram analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.79</td>
<td><strong>0.70</strong></td>
<td>0.64</td>
</tr>
</tbody>
</table>
Tree 2

Extracted distances to the skeleton:

0.266716, 0.127605, 0.251002, 0.279558, 0.149499, 0.157297, 0.386155, 0.420355, 0.230684, 0.179613, 0.172837, 0.128327, 0.215654, 0.127744, 0.111911, 0.137577, 0.235504, 0.640062, 0.755468, 0.700239, 0.224241, 0.200297, 0.316748, 0.181179, 0.144813, 0.0990285, 0.375469, 0.36098, 0.501244, 0.363721, 0.199245, 0.107485, 0.203817, 0.597858

<table>
<thead>
<tr>
<th>Manual diameter</th>
<th>Fitted Cylinder</th>
<th>Histogram analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49</td>
<td>0.58</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Tree 3

Extracted distances to the skeleton:
0.650002, 0.749743, 0.714055, 0.813927, 0.813736, 0.63117, 0.637312, 0.443304, 0.593424, 0.618511, 0.679637, 0.840878, 0.793613, 0.848572, 0.673937, 0.809772, 0.844926, 0.216731, 0.350377, 0.434011, 0.403922, 0.425435, 0.309693, 0.344987, 0.355881, 0.331779, 0.325831, 0.403043, 0.286395, 0.293172, 0.276749, 0.311505, 0.320906, 0.537326, 0.468881, 0.428352, 0.447296, 0.352581, 0.330997, 0.459961, 0.497432, 0.442678, 0.296572, 0.184423, 0.202911, 0.248942, 0.29068, 0.283754, 0.268572, 0.287239, 0.341136, 0.280697
Tree 4

Extracted distances to the skeleton:

0.725887, 0.775373, 0.261406, 0.327809, 0.328019, 0.401058, 0.358835, 0.399781, 0.329532, 0.119925, 0.363308, 0.471553, 0.563972, 0.662181, 0.588763, 0.400629, 0.566729, 0.458945, 0.42123, 0.282464, 0.346705, 0.358602, 0.390081, 0.878211, 0.456918, 0.355306, 0.588144, 0.531811, 0.725515, 0.492928, 0.519753, 0.198048, 0.171393, 0.329787, 0.0405506, 0.274983, 0.324957, 0.207481, 0.726862, 0.689592, 0.340545, 0.335959, 0.393947, 0.377521, 0.375062, 0.30089, 0.390539
**Tree 5**

<table>
<thead>
<tr>
<th>Manual diameter</th>
<th>Fitted Cylinder</th>
<th>Histogram analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.54</td>
<td><strong>0.53</strong></td>
<td>0.43</td>
</tr>
</tbody>
</table>

Extracted distances to the skeleton:

0.208273, 0.30461, 0.306919, 0.0936047, 0.169689, 0.0806121, 0.109375, 0.17408, 0.333579, 0.110321, 0.176631, 0.121358, 0.240685, 0.090996, 0.205646, 0.161586, 0.114864, 0.07858, 0.225882, 0.304271, 0.0814365, 0.204366, 0.255246
Tree 6

Extracted distances to the skeleton:

80.45694, 0.267907, 0.379198, 0.252324, 0.29393, 0.130908, 0.285491, 0.176257, 0.107532, 0.129896, 0.0792109, 0.169119, 0.0847128, 0.413211, 0.105562, 0.106939, 0.136867, 0.146268, 0.156315, 0.19551, 0.152943, 0.253035, 0.130016, 0.152709, 0.288821, 0.232244, 0.157093, 0.299209, 0.408229, 0.400956, 0.489314, 0.19318, 0.358556, 0.385719

<table>
<thead>
<tr>
<th>Manual diameter</th>
<th>Fitted Cylinder</th>
<th>Histogram analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.51</td>
<td>0.38</td>
<td>0.55</td>
</tr>
</tbody>
</table>
Tree 7

It was not possible to extract a diameter of this tree, because of computational costs. The calculation took over 4 hours, because of the very complex structure of the tree. But still the stem was not extractable with the given input parameters of 1m minimum voxel size and 40% threshold. This should be seen in relation to the calculation times of 30-300 seconds for the other trees (see description of the test setting in 4.3).

<table>
<thead>
<tr>
<th>Manual diameter</th>
<th>Fitted Cylinder</th>
<th>Histogram analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.82</td>
<td>No result</td>
<td>No result</td>
</tr>
</tbody>
</table>

Tree 8

No diameter was measured, because of the previous discussed reasons.

<table>
<thead>
<tr>
<th>Manual diameter</th>
<th>Fitted Cylinder</th>
<th>Histogram analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.82</td>
<td>No result</td>
<td>No result</td>
</tr>
</tbody>
</table>

4.4.2 Observations

- The test setting was done with 1m voxel size and 40% threshold. A better noise behavior can be achieved by using a smaller voxel size that resolves smaller structural details on the tree. But an improvement of the pre-filtering is also a possibility.
- An automatic processing of the data is technical possible on a standard PC.
- We recognized a significant amount of single measurements, which are less then the expected diameter. This is visible in the histogram.
• By choosing the first peak in the histogram from the back, we got good results. But in cases with fewer points (<30) the cylinder fitting was better. In noisy stems the Histogram analysis behaved better.
• The first proposed method to fit an ellipse with a direct ellipse fitting approach [35] to measure the stem thickness didn't give sufficient results. But it is not clear if it is due to implementation errors or due to the method.
• Two trees (tree7 and tree 8) were not possible to analyze with our test setup.

5. Conclusions

The main research question, whether the stem diameter is extractable from the FLI-MAP400 data is answered with a clear yes. The possibility to geometrically extract the stem out of the data leads to short computation times (30-300 seconds with the chosen test setting in 4.3.), because it is possible to work on a very small subset of the data. No empirical estimation is necessary, which means that no knowledge of the species needs to be collected in expensive field work. This can greatly reduce the costs.

All our investigated methods for automatic extraction are already available as prototypes or in standard software. For the cylinder fitting Cyclone 5.7 was used and for the tree delineation TerraSolid was used in combination with own software. It was shown furthermore that pre-filtering of the data is not always necessary, because the skeletonization algorithm is quite robust to noise and outliers. Still, pre-filtering can help in extreme cases.

• We used the possibilities of cylinder fitting in Cyclone 5.7 to show existing (semi-) automatic methods. In most cases the histogram analysis behaved better. Furthermore, the cylinder fitting can be interpreted as manually obtainable results using standard software.
• The average deviation of the cylinder fitting based on the 6 trees giving a result is 12.33 cm. Histogram analysis gives a far better average result with just 8.17 cm deviation from the manual field measurement.
• To be able to compute reliability we suggest a large field measurement. From the limited number of test cases we can not give reliability.
• According to the in between communication with Rijkswaterstaat our test cases cover the most relevant cases. In additionally trees on the forest border where used to simulate incomplete or extreme data sets.
• None of the investigated possibilities in the literature has shown the potential to extract the stem directly or geometrically from the data.
Much has been done in quantitative determination of vegetation friction in floodplain areas. However, most of this work is based on artificial and real vegetation at a laboratory scale. Extrapolating, we expect that 10 cm precision in stem thickness measurements would be sufficient to up-scale the vegetation friction model to floodplain scale.

70 points per square meter seem to sufficient to extract the stem diameter with 10 cm precision. With higher densities the measurement precision will further improve because smaller voxel sizes will be possible.

Seed point selection for tree segmentation can be done automatically using local maxima filtering. This is usually followed by a detailed analysis using neighboring maxima. This is a common approach which relies on maximum height points of the canopy surface. However, it is believed that with higher density of FLI-MAP data more efficient approach of tree detection can be produced.

The overall conclusion is that the FLIMAP data shows the potential to measure the stem diameter in breast height automatically. Compared to the values in literature the overall estimation error of less than 10cm in the stem diameter is good. Except for the extreme case of tree number 7 the stem was extracted correctly. But a change to the test setting will probably solve this problem, but in practice it will be faster to measure the extreme cases by hand. It should be investigated how many of these extreme cases are present in practice.

We want to mention at the end of this report some recommendations, if this method should be implemented:

- Setting the seed points for the region growing is still far away from an optimized solution and should be further developed
- Research on how to reliably remove the ground from the data should be done. Removal is needed to reduce the calculation time of the subsequent analysis.
- It is expected that after removing the stem, the remaining part of the skeleton can be used to estimate the crown size. This can be done by calculating the convex hull over the remaining maxima/minima in the graph. This will give another important forest parameter with the same method.
- The potential of the investigated method is to further extract the crown volume/diameter and the height of the tree. Good results are expected.
- It is further expected that in most cases the extent of the crown can be detected. This will lead to a detectable stem length and therefore together with the stem diameter to the economically useful biomass of the tree.
- Smaller voxel sizes can improve the result at the expense of longer calculation time, and may lead to results for the unsolved cases in our test. If the voxel size is reduced to the half the calculation time will be increased by factor 4.
• A smaller voxel size should be more robust in case of noisy data around the breast height (e.g. tree 2 and 4).
• It seems possible to parallelize our algorithm. In that case, Amdahl's law gives the upper bound of the performance increase factor as the number of voxel cells divided by 6. Practically a factor 10 is possible in our opinion.

Some issues in case of putting this method on the market:

1. A validation of the measuring method should be done on a huge test (more than 100 trees), to get information about reliability. We do not know now if it is always easy to detect the diameter.
2. It should be investigated whether an adaptive voxel size can improve the result in computation time and accuracy. Until now a fixed value was chosen.
3. Can the full data be handled in a Software System? Maybe already existent at Fugro or Delfttech?
4. Is it possible to export a model of the tree to a DTM Software? E.g. a model of the crown size and the stem, to give a bigger value to the method. Are there more applications?
5. The optimization either to a parallel working algorithm or to a memory and time efficient algorithm. Until now it is only optimized in terms of running time.
6. Investigate whether the all the unsolvable cases are automatically detectable, so that they can be exported for hand measuring to a standard software like Cyclone from Leica.
6. References


Diedershagen Oliver, et al. (2003) Combining Lidar and GIS Data for the extraction of forestry parameters.


Opitz, D. W., and R. R. J. S. Blundell (2006) Automated 3d feature extraction from terrestrial and airborne LiDAR, ed. S. Lang, T. Blaschke, and E. Schöpfer, vol. XXXVI. Salzburg University, Austria, ISPRS.


