| **Benchmarking under- and above-canopy laser scanning solutions, including autonomous drones, for deriving tree attributes in boreal forests** |
| --- |
| **Introduction:**  Detailed information regarding forests is required for utilizing them for economic purposes, while simultaneously maintaining biodiversity and their carbon sink properties [1]. For this purpose, individual-tree-level forest inventories are needed. Such inventories require accurate field reference for main tree attributes (diameter, volume, height and location), and should be fast to collect from a large area.  In this study, we compared the accuracy of the tree attributes and location automatically derived from point clouds of several laser scanning systems, operating both under- and above the forest canopy to provide this reference.  **Methods:**  The benchmark was performed on test sites located in Evo, Finland. Six m plots were used for the tree attribute benchmark, and a 800-m-long positioning track for evaluating the accuracy and precision of the positioning. The forest conditions varied from sparse, managed boreal forest mainly consisting of Scots pine (*Pinus sylvestris*) to dense natural boreal forest with a mix of coniferous and deciduous trees.The plots were categorized into easy and difficult plots based on the tree density and tree composition.  We utilized an automatic tool [2] for deriving the tree attributes and location, along with a novel bias compensation method to calibrate out the bias caused by the finite width of the laser beam.  We compared several state-of-the-art mobile laser scanners (MLS) operating under the forest canopy, and an airborne laser scanner (ALS) flying approximately 100 m above the canopy. The MLS systems included handheld devices and autonomous under-canopy drones, both in-house developed and commercial.  **Results:**  The positioning accuracy and precision (RMSE) of the ALS was <5 cm horizontally, and <10 cm vertically. The positioning precision of MLS devices were approximately 15 cm for the full positioning track and 5-15 cm for a half-track.  For the best performing MLS systems, the accuracy of the derived tree attributes; stem curve, diameter at breast height (DBH), stem volume and tree height ranged from 5–10 % RMSE for all attributes except for tree height and volume in the densest plots, with high understory vegetation, where the error was approximately 20 %. The accuracy of high-density ALS data was 10–25 %. The bias compensation reduced the bias of the tree diameter estimates by 55–99 %.  **Conclusion:**  The positioning accuracy and precision of high-density ALS was equal or better than the traditional field reference collected with a total station, while being orders of magnitude faster to collect from a large area, and thus can be used as a reference in future studies. The precision of the under-canopy laser scanners were also sufficient to unambiguously distinguish neighboring trees, which is required for use in an individual-tree-level forest inventory. However, their ability to localize themselves in a global frame was lacking.  The accuracy of the derived tree attributes from the most accurate under-canopy laser scanner systems were sufficient for use as a reference for individual-tree-level inventories (<10 % RMSE). The laser scanners with high beam divergence (and ALS) did not reach the required accuracy even with the help from the bias compensation.  **References:**  [1] Prasad, A., Pedlar, J., Peters M., McKenney, D., Iverson, L., Matthews, S., Adams, B., 2020, Combining US and Canadian forest inventories to assess habitat suitability and migration potential of 25 tree species under climate change. *Divers Distrib*. 26: 1142–1159.  [2] Hyyppä, E., Kukko, A., Kaijaluoto, R., White, J.C., Wulder, M.A., Pyörälä, J., Liang,  X., Yu, X., Wang, Y., Kaartinen, H., Virtanen, J.P., Hyyppä, J., 2020. Accurate  derivation of stem curve and volume using backpack mobile laser scanning. ISPRS  Journal of Photogrammetry and Remote Sensing 161, 246–262. |