



International benchmarking of terrestrial laser scanning approaches for forest inventories

Xinlian Liang^a, Juha Hyypä^a, Harri Kaartinen^{a,b}, Matti Lehtomäki^a, Jiri Pyörälä^{a,d}, Norbert Pfeifer^c, Markus Holopainen^{a,d}, Gábor Brolly^e, Pirotti Francesco^f, Jan Hackenberg^{g,h}, Huabing Huangⁱ, Hyun-Woo Jo^j, Masato Katoh^k, Luxia Liu^l, Martin Mokroš^{m,n}, Jules Morel^o, Kenneth Olofsson^p, Jose Poveda-Lopez^q, Jan Trochta^r, Di Wang^c, Jinhu Wang^s, Zhouxi Xi^t, Bisheng Yang^u, Guang Zheng^v, Ville Kankare^{a,d}, Ville Luoma^{a,d}, Xiaowei Yu^a, Liang Chen^a, Mikko Vastaranta^{a,d,w}, Ninni Saarinen^{a,d}, Yunsheng Wang^{a,*}

^a Department of Remote Sensing and Photogrammetry, Finnish Geospatial Research Institute, 02431 Masala, Finland

^b Department of Geography and Geology, University of Turku, 20014 Turku, Finland

^c Department of Geodesy and Geoinformation, Technische Universität Wien, 1040 Vienna, Austria

^d Department of Forest Sciences, University of Helsinki, 00014 Helsinki, Finland

^e Institute of Geomatics and Civil Engineering, Faculty of Forestry, University of Sopron (former University of West Hungary), H-9400 Sopron, Hungary

^f CIRGEO—Interdepartment Research Center of Geomatics, University of Padova, 35020 Legnaro, PD, Italy

^g Biogéochimie des Ecosystèmes Forestiers, INRA, 54280 Nancy, France

^h Laboratoire d'Inventaire Forestier, Institut géographique national (IGN), 54250 Nancy, France

ⁱ State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, 100101 Beijing, China

^j Environmental GIS/RS Lab., Division of Environmental Science & Ecological Engineering, Korea University, 02855 Seoul, South Korea

^k Forest Measurement and Planning Laboratory, Agriculture Faculty, Shinshu University, 399-4598 Nagano Pref., Japan

^l Institute of Forest Resource Information Techniques, Chinese Academy of Forestry, 100091 Beijing, China

^m Department of Forest Management and Geodesy, Technical University in Zvolen, 96053 Zvolen, Slovakia

ⁿ Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, 16500 Praha, Czech Republic

^o Institut Français de Pondichéry – Laboratoire des Sciences de l'Information et des Systèmes, India/France

^p Department of Forest Resource Management, Swedish University of Agricultural Sciences, 901 83 Umeå, Sweden

^q Treemetrics, Cork, T12 CCN3, Ireland

^r Department of Forest Ecology and Department of Landscape Ecology and Geoinformatics, Silva Tarouca Research Institute for Landscape and Ornamental Gardening, 602 00 Brno, Czech Republic

^s Department of Geoscience and Remote Sensing, Delft University of Technology, 2628CN Delft, The Netherlands

^t Department of Geography, University of Lethbridge, T1K3M4 Lethbridge, Canada

^u State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, University of Wuhan, 430079 Wuhan, China

^v International Institute for Earth System Science, Nanjing University, 210023 Nanjing, China

^w School of Forest Sciences, University of Eastern Finland, 80101 Joensuu, Finland

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ABSTRACT

The last two decades have witnessed increasing awareness of the potential of terrestrial laser scanning (TLS) in forest applications in both public and commercial sectors, along with tremendous research efforts and progress. It is time to inspect the achievements of and the remaining barriers to TLS-based forest investigations, so further research and application are clearly orientated in operational uses of TLS. In such context, the international TLS benchmarking project was launched in 2014 by the European Spatial Data Research Organization and co-ordinated by the Finnish Geospatial Research Institute. The main objectives of this benchmarking study are to evaluate the potential of applying TLS in characterizing forests, to clarify the strengths and the weaknesses of TLS as a measure of forest digitization, and to reveal the capability of recent algorithms for tree-attribute extraction. The project is designed to benchmark the TLS algorithms by processing identical TLS datasets for a standardized set of forest attribute criteria and by evaluating the results through a common procedure respecting reliable references. Benchmarking results reflect large variances in estimating accuracies, which were unveiled through the 18 compared algorithms and through the evaluation framework, i.e., forest complexity categories, TLS data acquisition approaches, tree attributes and evaluation procedures. The evaluation framework includes

* Corresponding author.

E-mail address: yunsheng.wang@nls.fi (Y. Wang).

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three new criteria proposed in this benchmarking and the algorithm performances are investigated through combining two or more criteria (e.g., the accuracy of the individual tree attributes are inspected in conjunction with plot-level completeness) in order to reveal algorithms' overall performance. The results also reveal some best available forest attribute estimates at this time, which clarify the status quo of TLS-based forest investigations. Some results are well expected, while some are new, e.g., the variances of estimating accuracies between single-/multi-scan, the principle of the algorithm designs and the possibility of a computer outperforming human operation. With single-scan data, i.e., one hemispherical scan per plot, most of the recent algorithms are capable of achieving stem detection with approximately 75% completeness and 90% correctness in the easy forest stands (easy plots: 600 stems/ha, 20 cm mean DBH). The detection rate decreases when the stem density increases and the average DBH decreases, i.e., 60% completeness with 90% correctness (medium plots: 1000 stem/ha, 15 cm mean DBH) and 30% completeness with 90% correctness (difficult plots: 2000 stems/ha, 10 cm mean DBH). The application of the multi-scan approach, i.e., five scans per plot at the center and four quadrant angles, is more effective in complex stands, increasing the completeness to approximately 90% for medium plots and to approximately 70% for difficult plots, with almost 100% correctness. The results of this benchmarking also show that the TLS-based approaches can provide the estimates of the DBH and the stem curve at a 1–2 cm accuracy that are close to what is required in practical applications, e.g., national forest inventories (NFIs). In terms of algorithm development, a high level of automation is a commonly shared standard, but a bottleneck occurs at stem detection and tree height estimation, especially in multilayer and dense forest stands. The greatest challenge is that even with the multi-scan approach, it is still hard to completely and accurately record stems of all trees in a plot due to the occlusion effects of the trees and bushes in forests. Future development must address the redundant yet incomplete point clouds of forest sample plots and recognize trees more accurately and efficiently. It is worth noting that TLS currently provides the best quality terrestrial point clouds in comparison with all other technologies, meaning that all the benchmarks labeled in this paper can also serve as a reference for other terrestrial point clouds sources.

1. Introduction

Forest field inventory holds a central role in all forest research, monitoring and managements that rely on knowledge of forest structure, distribution and dynamics over time. Field inventories are conducted in sample plots, where tree information is usually collected through tree-by-tree measurements (i.e., plot-level inventory). Forest field inventories can be costly since the field measurements require many efforts and resources, consequently limiting the amount of field inventories that can be afforded. Attempts to improve the field inventory efficiency started ever since field inventory began. Countless techniques, instruments, and protocols have been introduced yet progress has been slow, until a laser-based measuring instrument called terrestrial laser scanner became practically available.

The first commercial terrestrial laser scanner was introduced to the market in 1998. It automatically measures the surrounding three-dimensional (3D) space using millions to billions of 3D points. During the past two decades, the hardware has experienced rapid improvement, marked by its rapidly decreasing size, weight and price as well as its constantly increasing spatial resolution and measurement speed. The current systems measure up to million-level points per second with maximum measurement distance of 100–300 m; the range precision is at a millimeter level, and the angular sampling capacity is less than 0.01° in both horizontal and vertical directions.

The major advantage of applying terrestrial laser scanning (TLS) in forest inventories lies in the digitization of the forest plots accurately, rapidly, automatically and in detail at millimeter-level. In addition to the regular tree attributes measured in practical field inventories, e.g., the diameter at breast height (1.3 m, DBH) and tree height, more detailed tree attributes, such as the stem curve or taper curve (stem diameter as a function of height) that reveals the wood productivity and quality yet difficult to acquire non-destructively in the field, can be derived from TLS with high degrees of accuracy and cost efficiency (Liang et al., 2014b).

Tremendous efforts have been put into research to investigate the automated interpretation of TLS data and to establish best practices for using TLS. In the past 20 years, significant progress has been made in deriving tree- and stand-level attributes from TLS data to depict forest productivity, evolution and ecological functions. Early studies around the year 2000 (Erikson and Karin, 2003; Lovell et al., 2003; Simonse

et al., 2003; Aschoff and Spiecker, 2004; Hopkinson et al., 2004; Pfeifer et al., 2004; Parker et al., 2004; Schütt et al., 2004; Thies et al., 2004; Watt and Donoghue, 2005) explored the potential of measuring tree attributes using TLS. More recently, TLS has been shown to be capable of determining several high-quality tree attributes that are not directly measurable using conventional tools, such as the stem curve (Liang et al., 2014b). Tree-/plot-level stem volume and biomass components were also shown to be estimated at accuracy levels that are similar to those of the best national allometric models (Yu et al., 2013; Kankare et al., 2013; Astrup et al., 2014; Liang et al., 2014b).

However, the significant variance in the hardware properties, the scanning setups, the forest structures, and in the evaluation criteria and procedures among the reported studies has made reliable assessment of the performances of TLS for forest inventory extremely difficult. For example, as a fundamental criterion of TLS-based forest in situ observation, the percentage of detected trees from multi-scan TLS data ranged from 20% to 100% at the plot level as reported in previous research (Maas et al., 2008; Strahler et al., 2008; Broly and Kiraly, 2009; Murphy et al., 2010; Lovell et al., 2011; Yao et al., 2011; Liang et al., 2012; Lindberg et al., 2012; Astrup et al., 2014; Olofsson et al., 2014). Considering the diversity of the elementary components in the reported studies, such literature-based statistics do not reflect the capability and the overall performance of TLS due to the lack of a common frame of reference.

A proper understanding of the performance of TLS for forest in situ inventory can only be achieved when certain conditions are satisfied: that identical TLS data are processed; that common plot- and tree-level forest attribute are extracted; and that, the results from the algorithms are evaluated with reliable reference information utilizing standardized evaluation procedures. Under such conditions, all the algorithms are projected to a unique frame of reference, and an assessment of the status quo of the TLS-based forest inventory can be conducted by comparing the attribute extraction results of different algorithms.

As such, an international benchmarking study of TLS in forest inventories (TLS benchmarking) was launched in 2014 by the European Spatial Data Research Organization (EuroSDR) and partly funded by the European Community's Seventh Framework Programme Project Advanced_SAR. The TLS benchmarking aims to clarify the potential and current status of the TLS application in field inventories by evaluating methodologies on the basis of a standard evaluation procedure and a

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