land

Article

Adoption of Digital Aerial Photogrammetry in Forest Planning: A Case Study of Canavese Forestry Consortium, NW Italy with Technical and Economic Issues

Enrico Borgogno-Mondino [1], Samuele De Petris [1,*], Filippo Sarvia [1], Evelyn Joan Momo [1], Fabio Sussio [2] and Paolo Pari [2]

[1] Department of Agricultural, Forest and Food Sciences, University of Turin, L.go Braccini 2, 10095 Grugliasco, Italy
[2] DigiSky S.r.l., Strada Vicinale della Berlia 500, Turin Aeritalia Airport (LIMA), 10146 Turin, Italy
* Correspondence: samuele.depetris@unito.it

Abstract: The forestry sector has been significantly affected by the recent advances in geomatics. Photogrammetric aerial acquisitions provide full coverage of forests, making possible a wall-to-wall mapping of the main forestry key variables, such as tree height and tree density, needed for forest planning and management purposes. This work summarizes the role that digital aerial photogrammetry (DAP) is expected to have in the forest planning context and analyzes the main products from DAP that are significantly required. According to their technical features, some strategies are proposed to program acquisitions in order to consciously set operational parameters needed for obtaining accuracy of measures compliant with forest planning requirements. Admitting that, in most cases, forest planners externalize DAP acquisitions to flying companies, the authors propose simple strategies for making an ex-post evaluation of flight conditions through a conscious processing of the external orientation parameters of images resulting after the bundle adjustment. Theoretical aspects are exemplified with reference to a practical case study relying on an aerial acquisition that, in 2019, the Canavese Forestry Consortium (NW Italy) made to support the ongoing redaction of its new forest plans. Finally, some economic concerns are presented to demonstrate the capability of this technique to absorb the most of costs associated with ground surveys, especially when large areas have to be investigated. In particular, about 66% of cost savings were found when comparing DAP-based forest mapping to traditional forest inventory strategies.

Keywords: aerial photogrammetry; forest plan; forest inventory; photogrammetric points cloud; ortho-mosaic; product requirements in forestry

check for updates

Citation: Borgogno-Mondino, E.; De Petris, S.; Sarvia, F.; Momo, E.J.; Sussio, F.; Pari, P. Adoption of Digital Aerial Photogrammetry in Forest Planning: A Case Study of Canavese Forestry Consortium, NW Italy with Technical and Economic Issues. *Land* **2022**, *11*, 1350. https://doi.org/10.3390/land11081350

Academic Editors: Myroslava Lesiv, Linda See and Dmitry Schepaschenko

Received: 19 July 2022
Accepted: 17 August 2022
Published: 19 August 2022

1. Introduction

A wide variety of products and services provided by forests require the strengthening of the production chain to economically guarantee tangible and intangible benefits. The main weaknesses appear to concern forest management and harvesting sectors [1,2] where it is, therefore, important to encourage the implementation and integration of information and communication technologies [3]. The systematic adoption of new technologies by forest companies, technicians, owners and managers can be achieved only if proper tools are supplied. These are expected: (i) to perform complex analyses of forest and territorial data according to easy and economically convenient approaches; (ii) to generate reliable information through the adoption of standardized and reproducible procedures, aimed at guaranteeing transparency of decisions; (iii) to improve interactions among the main players of the forestry sector (technicians, policy makers, local communities). An almost complete knowledge of existing forest resources is basic for a technically oriented and optimal policy addressed to applying holistic (multifunctional) forest management [4]. From this point of view, geographical data and Geomatics can play a fundamental role [5,6].

It is a fact that the forestry sector, like many others related to environmental management, has been significantly affected by the recent advances in Geomatics. Technologies like GNSS (Global Navigation Satellite Systems) for precise positioning of ground observations, aerial and satellite remote sensing and digital photogrammetry for mapping both geometry and properties of forests, and GIS (Geographical Information System) for synthesizing all the information and making decisions are currently widely used tools in the forestry context, especially for addressing future management choices and planning interventions [2]. A great variety of applications exists concerning different scales of analysis. It is worth reminding here of the rigorous definition that Geomatics gives to the concepts of "small" and "large" scale maps. A small scale is that needed to map wide areas, where the detail level (resolution) is expected to be lower (e.g., 1:100,000). A large scale is that used when detailed maps of limited areas are required to focus on specific territorial elements (e.g., 1:2500). As far as applications are concerned, these range from management tasks, aiming at supporting forest and environmental planning, to analytical applications such as estimation of spatially distributed features (e.g., biomass), clustering, or modelling of environmental phenomena [7–11].

The introduction into the market of medium-low-cost airborne imaging systems has significantly enriched the survey of vegetated areas. These new technologies can provide both spectral and geometric information for large areas, enormously improving the ordinary and traditional surveying methods. In particular, digital aerial photogrammetry (hereinafter called DAP) is proposing new operational scenarios for measurement of morphometric and structural parameters of forest stands or individual trees [12,13]. Presently, photogrammetric measures represent one of the most accurate and fastest tools to estimate forest geometric parameters over wide areas with large scale mapping capability. In particular, survey speed determines a significant reduction of costs related to ordinary ground measures, suggesting an extensive adoption of this technique in the forestry sector that is, notoriously, a low-income sector. Additionally, the availability of low cost multispectral sensors and medium-high geometric resolution satellite imagery (e.g., Copernicus Sentinel 2) makes possible an integration of spectral information with aerial surveys to generate a more complete knowledge of tree features [14,15], proposing a new paradigm for land management [16]. The success of the ongoing technology transfer process relies on the acquisition of proper native data from DAP or remote sensing (RS). This requires an adequate level of scientific consciousness of digital photogrammetry and positioning that, presently, appears as missing [17,18]. The ordinary workflows that DAP software accomplishes, in most cases, hides this lack of consciousness from unskilled users, making derived measures unreliable.

With these premises, this work is exactly intended to present a comprehensive analysis of the expected approach that one should apply when using DAP for forestry purposes. In particular, it supplies a sort of "how-to" document where all technical choices underlying flight planning for DAP are motivated according to the expected target. Furthermore, a preliminary economic comparison is given between traditional and DAP-based survey approaches. The paper is not a review, but is specifically intended to define general "best" practices for DAP adoption in the forestry sector, that appear to be often neglected while programming and operating flights for deriving the structural parameters of forests. To make theoretical discussions clearer and presenting practical effects that conscious choices can determine in arriving at results, a case study is used. It is worth highlighting that the case study is not the focus point of this paper; it is merely used to generate numbers that are expected to support the reader's interpretation of the work, thus improving his/her consciousness of the discussed issues.

According to this idea, the paper first summarizes the role that DAP is expected to have in the forest planning context and analyzes the main products from DAP that are mainly required. According to their technical features some strategies are proposed to program acquisitions in order to consciously set operational parameters needed for obtaining accuracy of measures compliant with forest planning requirements. Admitting that in most cases forest planners externalize DAP acquisitions to flying companies, the authors propose simple strategies for giving an ex-post evaluation of flight conditions through a conscious processing of the external orientation parameters of images resulting after bundle adjustment. Finally, some economical concerns are given to demonstrate the capability of this technique of absorbing most of the costs associated with ground surveys, especially when large areas have to be investigated.

Expected Role of Photogrammetry in Forest Planning

DAP in forestry is mainly thought to reduce ground survey-related costs, improving the precision and spatial continuity of estimates and frequency of surveys. These issues appear to be particularly interesting when developing new forest plans (FP) [19]. DAP can provide full coverage of a territory making possible a wall-to-wall mapping of key forestry variables (tree height, density and count) that are useful for forest planning and management purposes. This peculiarity makes it highly effective if compared with traditional ground plot-based surveys. The first examples of aerial imagery utilization for forestry purposes date back to the beginning of the 1920s [20,21]. Especially, three-dimensional (3D) data, needed to describe tree/canopy height, have shown a great potential in forest inventories (FI) [22]. In the past 20 years, airborne laser scanning (ALS) has been widely used for forest inventories and has become the standard data source in many countries [23–27]. Nevertheless, ALS systems are expensive, making them cost-effective only if used over very large areas [28]. Consequently, photogrammetric-based approaches have become popular as an alternative technique to obtain 3D information on forest structure, offering significant cost savings [29]. Photogrammetry is known to suffer from some limitations mainly related to the possibility of describing solely the upper layer of forests, limiting ground information that can be obtained only to where large vegetation gaps are present. Nevertheless, pre-existing data describing the under-tree ground surface, possibly from past ALS acquisitions, can be used to fill this gap. This type of data integration has been thoroughly discussed by [12], stressing its potential for cost-effective forest inventory and FP updates. In spite of the proven complementarity of Light Detection and Ranging (LiDAR) and photogrammetry [30,31], some recent attempts have been made to derive relevant metrics for forest inventory totally based on terrestrial and aerial photogrammetry [32–35]. Photogrammetry was also used for forest health monitoring [36–38], species classification [37], biodiversity assessments [39,40] and tree stability evaluation [15]. Inventories based on DAP can be referred to as enhanced forest inventories (EFI). They have proved to be particularly helpful in FP [41]. With respect to traditional forest inventories, EFIs provide some advantages, mostly related to structural forest characterization. DAP data for EFIs are increasingly becoming adopted and utilized in forest management as reference approaches to improve inventory content, as well as bridging gaps between strategic, tactical, and operational levels [42]. In Italy, ordinarily, FPs are regulated by regional laws and the planned forest areas (PFA) are defined and managed according to silvicultural prescriptions. PFA are mapped according to the prevailing forest utilization (e.g., timber production, natural protection, recreational). This tessellation criterion requires a ground survey for each forest stand aimed at measuring the main forest metrics. This is the most expensive operation in the FP framework, being highly time consuming. In fact, operators have to move across large and impervious areas looking for proper stands where metrics can be assumed to be representative of a wider part of the forest. Observations from ground surveys are used on which to base technical interventions that represent an important part of FP. With these premises, DAP should play a key role in improving economic saving [42].

This work is aimed at reviewing and structuring the DAP role within FP in the framework of a dendro-metric data survey, with special concern for the effectiveness and costs of the process. A sort of how-to discussion is presented about requirements, expected processing procedures and products of DAP in the forestry context, based on the authors' previous experiences. These general issues were exemplified with reference to an operative case study supporting the development of a new FP by the Canavese Forestry Consortium

(Piemonte Region, NW Italy). It is not the authors' intention to compare the precision of ground- and DAP-based surveys, since they retain that no dendro-metric measure from DAP can be assumed as reliable if not properly calibrated through adequate ground plots. No discussion is given of the abandonment of ground surveys; on the contrary, the authors long for a proper integration of ground surveys with DAP. From this point of view the expected added value from DAP will be the reduction (not elimination) of the number of ground plots and a higher completeness of forest stands description. Consequently, the only comparison here proposed is the economic one that is intended to supporting the convenience of a proper technology transfer of DAP to the FP sector. The precision of DAP-based surveys can be assumed to be that estimated during the DAP measurement calibration step, relying on comparison with the reference ground plots.

2. Materials and Methods

2.1. Photogrammetric Products Useful for Forestry Applications

Several experiences were reported in the literature regarding DAP-based forest applications. They mostly deal with the exploitation of Digital Surface Models (DSM) and ortho-mosaic for forest inventory [12,34]. These, in fact, are the basic data that DAP provides, supporting most deductions. The authors are aware that the most advanced applications of LiDAR and DAP rely not exactly on DSM and ortho-mosaic exploitation, but on the direct processing of point clouds to obtain forest estimates. Nevertheless, currently in Italy the operational/productive sector is still referring to and requiring more easy and accessible outputs than heavy point clouds. DSM and ortho-mosaics, from this point of view, appear to be more compliant with users' community requirements. Consequently, given the explicit goal of this paper of being a how-to guide for best practices in the forestry operational/production field, the authors have preferred to focus on these two products from DAP. It is worth reminding that DSM are raster data obtained by regularization of point clouds, whose Ground Sampling Distance (GSD) strictly depends on point cloud density (points/m^2). DSM and Digital Terrain Models (DTM) are the basis of Canopy Height Models (CHM) computation [43,44]. They are obtained by grid differencing comparing a DSM and a DTM. In general, it can be assumed that, in forests, DTM does not change quickly over time, giving a representation of the ground surface height over longer times. On the contrary, DSM, mapping the top of the trees' height, is expected to change with vegetation cycles and age. This situation makes it possible to admit that the generation of a new DSM can be enough for an updated mapping of CHM. In fact, a new DSM can be compared with a previously existing DTM to generate sufficiently accurate estimates of updated forest geometries. This assumption is basic when working with DSM from DAP, since there is no chance of having other information on the forests if not the one related to the very top of the canopy; no multiplane forest stand can be reasonably mapped by DAP, that, therefore, can be successfully used only in monoplane stands. For other, more complex, situations, aerial LiDAR still remains the reference technique [45,46]. Under these constraints, CHM represents a common tool to derive tree parameters. Starting from a CHM, tree apex detection is, in general, the first step to be achieved. Two main types of algorithms are commonly adopted based on local operators (sliding windows) in charge of looking for CHM local maxima [47]. Once local maxima have been identified, image segmentation algorithms [48], centered around those points, can be adopted to border single tree crowns. Ordinarily, a local-maxima approach is adopted to count trees and to obtain the correspondent height estimate from CHM. To obtain additional information on tree crown, e.g., minimum/maximum crown height, crown radius, crown width, crown shape, segments from segmentation are needed. It has to be considered that segmentation is highly sensitive to its threshold parameters, making crown delineation poorly reliable. In general, multiple trials have to be carried out to find the optimal value, whose identification strictly depends on the a priori silvicultural knowledge of the area. Additionally, DSM is needed to generate image ortho-mosaics from native acquisitions [49]. In the forestry sector, true color or multi-spectral ortho-mosaics are mainly useful to recover information about land cover and supporting photointerpretation of land features (e.g., forest and pastures tares). Diameter at-the-breast height (DBH) and wood volume (WV) are fundamental silvicultural measures used for characterizing trees. DBH is needed to compute WV or to estimate above ground biomass. Aerial survey cannot provide this information directly and allometric functions relating DBH, or WV, with other easy-to-measure dendro-metric parameters (e.g., tree height), are required. These models, commonly used in forestry [50,51], rely on regressive functions calibrated using ground data and relating tree morphometric parameters (e.g., DBH, WV, tree height, crown width) [52]. An example is reported in Figure 1 where tree height, as retrieved by DAP, is assumed as predictor of WV. According to EFI approaches, proper allometric models can be used to derive DBH and WV from tree height [53]. Some limitations still persist mainly related to tree counting. Conversely, tree height as computable from CHM proved to be more accurate than that from ordinary ground surveys. DAP allows the computation of tree height value with an accuracy (σ_h) generally higher than that of ground surveys [54].

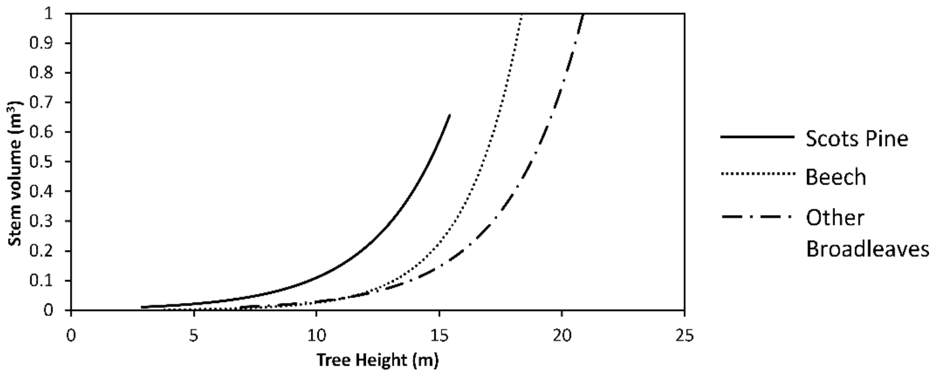

Figure 1. Three dendro-metric functions provided by [43] relating tree stem volume to tree height.

2.2. *Programming the Flight*

The identification of the most suitable sensors, in terms of spectral and geometric characterization of forests, has great importance when moving from the research to the operational/economic. Ongoing technological advance has drastically reduced the cost of sensors, making them consistent with small and medium-sized companies' economic requirements. The market offers many choices for sensors, ranging from ordinary cameras to specifically mapping devoted examples (e.g., Vexcel Ultracam Leica DMC, etc.). Even if the latter show technical features enormously better than ordinary digital cameras, these could not be entirely appreciated in the forestry sector where a decametric precision is needed to make a measure exceptional. Since they are commonly associated with a cost level significantly higher than that of ordinary digital cameras, their adoption in the forestry field, from a technological transfer point of view, is limited. Consequently, in this work, the authors focused on ordinary digital cameras, assuming them to be consistent with the cost level associated with FP. Currently, most Red Green Blue (RGB) cameras (reflex type and fixed focal length, particularly) have technical features that fully satisfy aerial photogrammetric survey requirements in forestry, where morphometric characterization of single trees is now possible, as proved by several experiences in the literature [15,53,55], with a proper level of precision (more than 90% of tree detection accuracy). The definition of a repeatable and standardized method for planning and operating acquisitions is mandatory to guarantee data integration and satisfactory accuracy requirements. The planning step of the flight is, consequently, basic in order to ensure proper acquisitions [56,57]. In particular, the following conditions have to be guaranteed: (a) a proper geometric resolution of images, that has to be consistent with the minimum size of targets to be detected; (b) an adequate geometric scheme of block acquisition ensuring the target precision of the final measures; (c) a proper chromatic/spectral content has to be recorded depending on the chemical/physical properties that one wants to describe. Image geometric resolution, or GSD, defines the pixel size at the ground. Even if the major requirement is that GSD is consistent with the minimum mapping unit one has to detect, it also conditions the planimetric and altimetric accuracy of measures obtainable from the adjusted image block [58]. GSD can be computed according to Equation (1):

$$GSD = \frac{H}{f} \cdot p \tag{1}$$

where H is the above ground level flying height (AGL), f the focal length of the camera and p the size of the physical pixel (detector) of the camera. f and p are fixed once the sensor has been selected, while H is an operational parameter that has to be opportunely tuned when planning the flight. As far as geometric conditions of acquisitions are concerned, one has to consider that they directly affect both the efficiency of the Structure from Motion-Multiple View Stereo (SfM-MVS) [59] algorithms operating within photogrammetric software, and the precision of the obtainable measures. SfM-MVS algorithms are at the basis of tie points and dense cloud generation in modern software for digital photogrammetry. Their efficiency strictly depends on the degree of similarity that stereoscopic images show. This is higher when the overlap (both forward and side) is larger (shorter baselines and strip distance), making neighbor images more similar. This greatly favors image correlation algorithms used by SfM-MVS, permitting the detection of a greater number of homologous points. This is desirable during the image alignment step and during dense cloud generation. Unfortunately, short baselines are known to compromise vertical precision (Z coordinate) of point measures. The theoretical vertical precision (σ_z) for measures from oriented image blocks can, in fact, be computed by Equation (2) [60]:

$$\sigma_z = \frac{H^2}{f \cdot B} \sigma_p \tag{2}$$

where H is the AGL height, B the baseline, f the camera focal length and σ_p the expected uncertainty in measuring image coordinates over the focal plane (a fraction of the physical pixel ranging between 0.2–0.5) [15].

For completeness of this discussion, one has to notice that SfM-MVS algorithms operate with not completely transparent computational steps, which moves actual accuracy estimates from the theoretical in unpredictable ways. Consequently, the a priori estimates of σ_z by Equation (2), based on a traditional photogrammetric approach working with nadiral acquisitions, has to be assumed as purely indicative. Nevertheless, previous experiences of the authors demonstrate that the estimated σ_z values were not so far from the actual ones [14,15] derived comparing tree heights from DAP to references ones obtained by ground surveys. Moreover, we have also to state that SfM-MVS algorithm proved to be high performing when oblique images are processed. In this case also, σ_z estimate escapes from the ordinary equations of traditional photogrammetry, making difficult to obtain a reliable a priori estimate. Since theoretical horizontal and vertical accuracies can be estimated before the flight, flying conditions can be tuned to satisfy metric requirements. In the forestry sector, to guarantee a proper consistency between DAP measures and existing maps, horizontal accuracy has to be higher than that expected for the map scale the work is intended for. It is worth remembering that the theoretical precision of a map, in Italy, can be set as equal to 0.2 mm at the scale of the map [61]. Consequently, a 1:1000 scale map and a 1:2000 scale map have an "expected" horizontal accuracy of 0.1 and 0.2 m, respectively. On the contrary, the vertical accuracy of measures from DAP, in forestry, has to be minimally consistent with that obtainable though ordinary ground measures. These, generally, are obtained using a hypsometer, i.e., an optical-mechanic lightweight instrument exploiting trigonometry to recover tree height. Precision is known to range between 1 and 5 m [53,62]. This makes it possible to desire a vertical accuracy of measurements from DAP (σ_z) smaller than 2 m. Concerning GSD, no optimal value can be set a priori in the agro-forestry sector, since this strictly depends on the application [63]. GSD must therefore be related to the expected forest features, such as tree crown geometry and size. GSD can be referred to both native images and DSM. The first, more directly related to the final ortho-mosaics (GSDo), is important to guarantee an adequate interpretability of forest stands. The second, related to DSM (GSDd), is the one that most dendro-metric measures rely on. GSDd can be reasonably admitted as being larger than GSDo, resulting from the regularization of the dense cloud that is generated by image intersection within photogrammetric software. Since points belonging to dense clouds are a subset of all image pixels, GSD_D has to be necessarily larger than GSDo. Consequently, GSDd is the most critical factor that has to be taken into account when programming the flight. The following considerations can be made: tree crowns can be assumed as varying between 12 m^2 and 150 m^2; their shape strictly depends on the stands one is going to survey. The shape can be considered with reference to the front section of a paradigmatic tree crown representative of the stand. Crown section can be approximated by a triangle having different apertures, depending on tree species (minimally, broadleaves and conifers). When programming the flight, one can focus on the height difference (Δh-Equation (3)) that corresponds to GSD_D. Δh can be estimated considering the local average slope of the crown as schematically reported in Figure 2.

$$\Delta h = \text{GSDd} \cdot \tan \alpha \tag{3}$$

where α is the local slope of the crown shape.

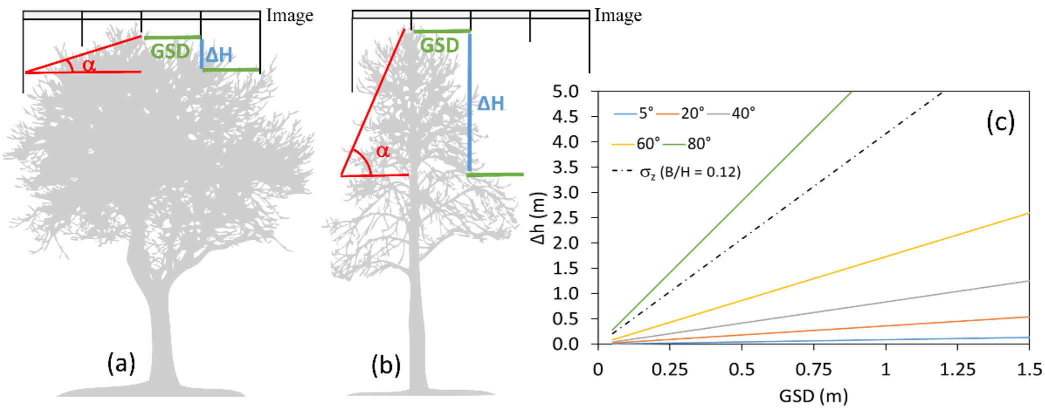

Figure 2. (**a**) Broadleaf tree; (**b**) conifer tree; (**c**) Δh is the height difference in crown geometry corresponding to the GSD size of DSM/CHM (GSDd). It depends on the α value. Broadleaves show α values reasonably ranging between 5° and 45°, while for conifers this is greater than 45°.

Generally, broadleaves crowns show sympodial form (i.e., ellipse like) determining low α angles (high triangle aperture); conversely, conifers show monopodial form (i.e., cone like) determining higher α angles [64–66]. Figure 2a,b schematically show this condition, giving evidence of the geometric relationship between GSDd and Δh. Figure 2c, instead, shows the numerical relationship between them. Operationally speaking, if the whole height variability of the tree crown has to be described, one has to guarantee that $\sigma_z < \Delta h$. It can be noticed that conifer stands require smaller GSDd, showing larger Δh values. For example, looking at Figure 2c and assuming σ_z = 2 m, a GSDd of about 1.2 m and a GSDd of about 0.4 m are enough to completely describe crown geometry of broadleaves (α angle generally < 45°) and conifers (α angle generally > 45°) stands, respectively. Once these reference values have been set for GSDd, and taking into account a cautionary efficiency of the SfM algorithm to generate dense clouds (e.g., one point every 10 image pixels), it is possible to hypothesize a reasonable value for GSDo = GSDd/10. According to the above-mentioned example, GSDo can be set at 0.12 m and 0.04 m for broadleaves and conifers, respectively.

The chromatic/spectral content of data strictly depends on the sensor whose selection is expected to be made according to the application one is going to face. An RGB true color image can be enough if a pure geometric survey is required for the mapping of dendro-metric parameters. A multispectral sensor is needed if tree species classification, or tree disease detection, are required; whereas, if the focus is on thermal anomalies mapping, energy balances or evapotranspiration estimates, a thermal camera, possibly coupled with a multispectral sensor, is the right choice [67–69]. Concerning data processing, when approaching spectral measures with the aim of deriving quantitative information about chemical/physical properties of surfaces (possibly comparable along time), one has to consider that raw data from sensors could not be directly used; a radiometric calibration of images is therefore mandatory to translate native spectral measures (quantized values of incoming radiance) into at-the-ground reflectance (optical multispectral sensors) or land surface temperatures (thermal cameras). Image radiometric calibration is expected to be achieved before image block bundle adjustment is run. Some open questions concerning the reliability of calibrated data from RPAS/airborne multispectral sensors are still to be answered [18]. Generally, radiometric data pre-processing is achieved using software that is supplied together with the sensor. This step involves the adoption, during the flight, of calibrated panels or sun irradiance measurement units [70]. These approaches are known to be approximated, thus excluding a rigorous recovery of at-the-ground reflectance. Furtherly, some additional doubts persist about the spectral degradation that could affect data when processed by photogrammetric software to obtain multispectral/thermal ortho-mosaics.

Time frequency of acquisitions is another key point in forestry. This defines the time step between two consequent acquisitions. Higher values are expected if one has to monitor forest stand dynamics (e.g., renovation, degradation). Differently, a single acquisition at the right moment along the growing season can be enough to derive dendro-metric information.

Another operative consideration is related to the vehicle adopted to survey vegetated areas by DAP (i.e., satellite, plane or remotely piloted aircraft system—RPAS). Its selection mainly determines the surveyable area's size. For example, high resolution satellite-based stereo pairs can generate elevation models over large areas but their temporal resolution is limited [49,71]. RPAS-based photogrammetric surveys are a very challenging issue, especially in a forest context [67]. The RPAS low-cost increases the user community of DAP surveyors. Unfortunately, due to battery autonomy, small areas can be surveyed limiting drone-based DAP for forest inventory [72]. In this context, plane-based DAP seems the most promising, since it guarantees a large area survey, fitting for forest inventory purposes [73]. Unfortunately, this type of DAP is limited to specialized companies due to the high cost of vehicles and skilled pilots.

2.3. Processing and Validating Data

DAP-based measures rely on the solution of images' exterior orientation obtained by bundle adjustment. This can be achieved by direct georeferencing if high accurate position and attitude data (exterior orientation parameters, EO) are available from GNSS + IMU (Inertial Measurement Unit) [74]. Unfortunately, this type of solution is associated with very expensive systems that in general reflect on final cost for acquisition. Moreover, even if operating by direct georeferencing, some surveyed ground points operating like GCPs or check points are desirable to ensure reliability of direct position and attitude measures. In DAP, low-cost applications (like those for forestry), direct georeferencing is often not compliant, and EO values are obtained through the numerical solution of a system of equations based on GCPs and Tie Points [75]. Given the reduced accuracy requirements of forestry measures (around the meter) and the objective difficulty of walking through large forested areas, it is highly desirable to avoid ground survey of GCPs. Consequently, to reduce costs and speed up the process, GCPs can be obtained from official existing geographical data having proper scale and accuracy. Stable territorial elements like building corners, road crossings, plinths, backhoes, etc.. are proper points to be selected as candidates for GCP. To further reduce times and efforts in data processing while validating numerical estimates of EO parameters, an effective strategy of accuracy assessment can be adopted relying on solely on GCPs. The leave-one-out procedure [76] can be a proper solution for this. This approach makes possible a generalization of precision values from GCP. This is based on the selective and sequential exclusion of a single GCP to obtain different bundle adjustment solutions, where the excluded GCP operates like a check point. The correspondent positional error can be therefore assumed as the one associated with a check point located in that position, and therefore used to generalize precision estimates of adjustment outside GCPs. While estimating potential accuracy of DAP from an oriented block, it is always desirable to consider separately horizontal and vertical components. In general, accuracy is computed by RMSE (Root Mean Squared Error), MAE (Mean Absolute Error) or standard error (SE). According to [77], MAE appears to be a more robust estimator of the actual accuracy of a model with respect to RMSE. SE remains the reference precision metric able to synthesize most of the error dispersion around its mean value. Consequently, MAE or SE are the accuracy measures we suggest a further step that the authors warmly suggest during data processing is the a posteriori validation of flight requirements, especially when commissioning acquisitions from external companies. This can be achieved by computing back the main flight parameters using the numerical estimates of the EO parameters. During this step one should with caution take into consideration maximum and minimum values of each parameter depending on the local topography of the imaged area. Minimally, the authors suggest computing back the following flight parameters: average baseline, average image overlaps (forward and side), maximum and minimum image scale, maximum and minimum GSD, maximum and minimum image footprint and the correspondent theoretical (expected) vertical accuracy. Maxima and minima values for image scale and footprints, GSD and vertical accuracy can be determined with reference to an available DTM, especially when AGL height significantly varies over the acquisition area. These parameters have then to be compared with those used during the redaction of the flight plan to validate it. If these checks provide a positive answer, the process can proceed with the generation of point clouds [29] and ortho-mosaics [78]. These are the main products that DAP is expected to generate and that most applications base their deductions on.

2.4. Economical Convenience of DAP in Forestry

The following key aspects of DAP products in EFI can be summarized: (i) DAP changes the paradigm in forest inventory, moving from the traditional ground survey based on punctual observations (plots) that are assumed as representative of a wider territorial context, to a continuous and dense 3D representation that makes possible tree crowns characterization at whatever position in the surveyed area. Thus, from a statistical point of view, DAP strongly reduces confidence intervals in forest inventory parameters such as tree density, basal area, tree volume, finally resulting in more accurate estimates; (ii) ordinary forest plots require a strong inference effort (at forest type level) difficult to be validated. Differently, EFIs allow a complete area description, supplying reasonable estimates of forest parameters in all PFA. On the other hand, DAP-derived products do not allow direct detection of tree species, tree diameter at breast height and, in general, timber quality. Therefore, some models are needed to give indirect estimates of these parameters from those that can be directly measured from a CHM. Few ground measures continue to be necessary in this context to opportunely calibrate and validate models relating direct and indirect measures. Nevertheless, the number of plots could be significantly lower than that required by ordinary FP. With these premises, a first economic assessment is here proposed comparing ordinary FI approaches and EFI, based on DAP products. The Piemonte Regional Forestry technical guidelines describe how to design forest plans (Regional Law n. 4/2009 art. 11 c. 2). They report that a representative number of forest plots have to be surveyed. This number relies on statistical concerns and can be obtained by Equation (3) (forest type dependent).

$$n = \left(\frac{t \cdot CV\%}{\varepsilon\%} \right)^2 \quad (4)$$

where *n* is the required number of plots, *CV*% is the coefficient of variation (in percentage) of the tree basal area [79]; ε% is the expected error expressed as a percentage; and *t* is the Student's *t*-value.

2.5. The Case Study

To give evidence of how the above-mentioned concepts can find application in the operational field, a case study was selected and analyzed. The aim was not to provide a description of the entire workflow, but to focus on the acquisition step, including post-flight validation of image blocks. In 2019, the Canavese Forestry Consortium (CFC), in partnership with the GEO4Agri Lab of the Department of Agriculture, Forestry and Food Sciences (DISAFA) of the University of Torino (Grugliasco, Italy) and Digisky s.r.l., a private company committed to DAP, conducted a photogrammetric survey aimed at supporting the development of its forest plans. The above mentioned players were commissioned for different tasks: CFC was in charge of providing auxiliary information concerning forests of interest; Digisky was in charge of programming and operating flights according to its ordinary procedures; DISAFA was in charge of processing data and testing consistency of actual flight parameters after the flight with those programmed by Digisky, including a verification of properness of acquisition for the expected forestry application. CFC was established in 2002 as the reference management player for forests located in the Canavese area (Piemonte region, northwest Italy). Forests managed by CFC (hereinafter called AOI) spread over 23 municipalities and have an area of 2142 ha (Figure 3). Chestnut is the prevalent tree species in the area.

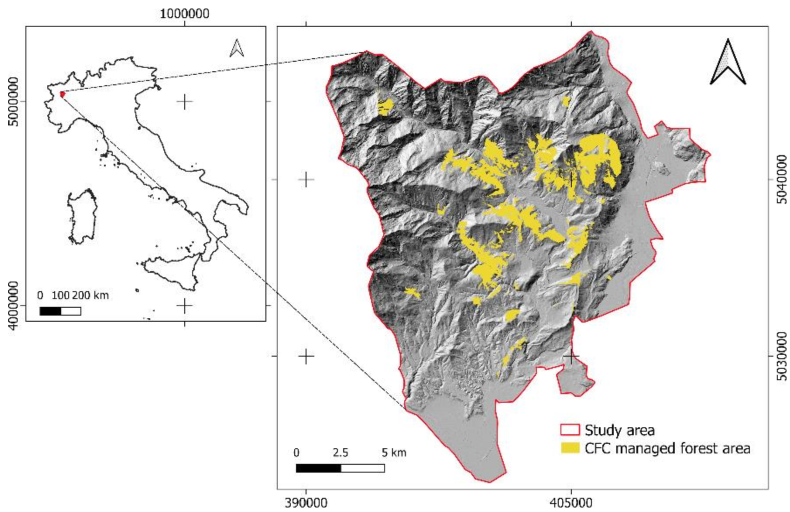

Figure 3. Study area in Italy (left). Area of Interest (AOI) where the forest plan had to be defined by CFC. In grey the hill shading of the SRTM 1 Arc-Second 30 m [80] (coordinate reference system is WGS 84/UTM zone 32 N).

2.6. Flight Plan

An aerial survey was operated in November 2019 to image part of the PFA (Figure 3). A correspondent photogrammetric block was planned and acquired by Digisky according to their ordinary workflow and criteria. According to the Digisky strategy, a flight plan was designed to satisfy accuracy and resolution requirements and to ensure proper overlapping conditions suitable for both optimizing SfM performance and minimizing costs of acquisition. The Phase-One iXM-RS150F RGB camera was used for all the acquisitions, having the following technical features: focal length = 50 mm, physical pixel size = 3.76 µm, sensor size = 53.4 × 40 mm. Aerial surveys were performed allocating the camera within the SkyMetry©/SmartBay© platforms by Digisky (Figure 4). SkyMetry© is an integrated solution which allows simultaneous data acquisition by different sensors: true color, multi-spectral, and thermal cameras. SkyMetry© is a good solution for high-resolution mapping of the territory and infrastructure. It permits an automatic mission planning depending on the geometric features of target areas and an optimized configuration of sensors. System strength relies on its high reactivity, as a mission can be planned and executed within a day. The web platform of the SkyMetry© system, after the acquisition plan is achieved, generates a series of files needed during the flight for automatic management of on-board avionics. SmartBay© thus manages the mission autonomously, supporting the pilot in following the proper routes to obtain the expected result (through the COD screen, Crew Operator Deck) and automatically enabling/disabling sensors. The system autonomously records metadata for image approximated positioning and orientation that are automatically pushed onto a flash memory located in the cockpit.

Figure 4. (**a**) SmartBay© platform; (**b**) Tecnam P92 JS aerial; (**c**) Phase-One iXM-RS150F RGB camera.

After the flight, DISAFA proceeded to adjust the block, to validate flight requirements and to produce a preliminary economical comparison between ordinary surveys and DAP in the surveyed area using average costs for the involved items.

3. Results

3.1. Flight Plan Design

Flight plan was defined by Digisky according to its ordinary workflow and strategies, taking care of the main requirements of images for forest applications. Planned values are reported in Table 1.

Table 1. Planned values of the main geometrical parameters for the operated flights.

Parameter	Value
Flying speed (km h^{-1})	165
Side overlap (%)	65
Forward overlap (%)	85
Nominal baseline (m)	192
Flight Line Distance (m)	598
Average AGL height (m)	1600
Average B/H ratio	0.12
Flight lines	14
Number of images	692
Nominal footprint (across track, m)	1709
Nominal footprint (along track, m)	1282
Nominal GSD_H (m)	0.12
Nominal vertical accuracy (σ_z m @ σ_p = 0.5 pixel)	0.50

Programmed conditions appeared to satisfy forest requirements for broadleaves. In fact, σ_z is consistent (better) with the accuracy of ordinary forest surveys for tree height determination. Concerning the base to distance ratio (B/H), in [81] σ_z is demonstrated to be inversely proportional to B/H: the larger the base, the smaller the Z error. In [82], the authors suggest that optimal B/H values for DTM/DSM generation should range between 0.5 and 1. According to Table 1, B/H ratio for the analyzed acquisition is expected to be equal to 192/1600 = 0.12 on average. This suggests that proposed forward overlap values (85%), compliant with SfM, significantly reduce theoretical Z accuracy. In fact, if a 0.5 value had been used for B/H, σ_z would have been equal to about 0.12 m, as against 0.5 m. Unfortunately, given the camera orientation on board the airplane (longer side across track), such a value would have determined a forward overlap of about 37%, making it impossible to guarantee stereoscopic conditions along the strip. These few simple arguments are intended to show how, necessarily, choices for a proper management of photogrammetric acquisitions are always the result of a compromise whose balancing must be given depending on the priority of the measures one is going to take. Within this framework, to cover AOI, Digisky acquired a total of 692 images sizing about 101 Gb.

3.2. Image Block Resection

DISAFA proceeded to solve image block orientation by bundle adjustment. Ten Ground Control Points (GCPs) were collected over the block. Imaged points associated with stable territorial elements (e.g., building corners, road crossings, plinths, backhoes, etc.) were recognized on available digital maps. As horizontal reference, the AGEA (Italian Agency for Payments in Agriculture) digital orthoimages were used. These are released in the WGS84 UTM32N reference system, were updated in 2018 and show an average GSD of 0.3 m. Positional accuracy is not declared, but it can be reasonably assumed as equal to 1 pixel (0.3 m). As vertical reference for GCPs, the DTM of the Piemonte Region was used. It is released with a GSD of 5 m and a vertical accuracy of ±0.3 m in ordinary areas and ±0.6 m in urban and forested areas. Both data were made available free of charge through the regional geoportal website (www.geoportale.piemonte.it (accessed on 3 August 2022)). Number, distribution of GCPs within the block and flight plane representation are shown in Figure 5.

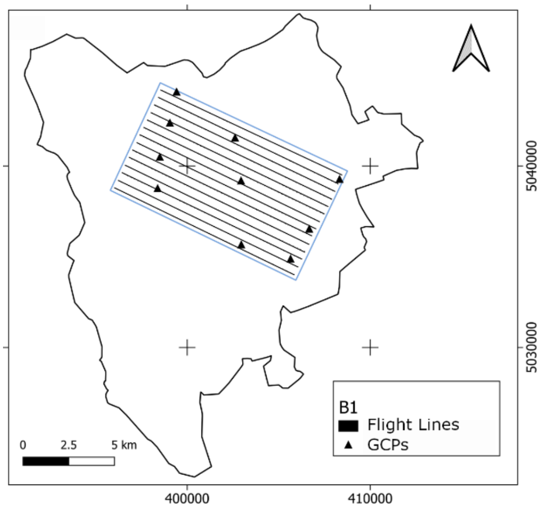

Figure 5. GCPs distribution within the B1 block (coordinate reference system is WGS 84/UTM zone 32 N).

Bundle adjustment was achieved by Agisoft Metashape 1.7.4 software that operates according to the SfM approach. It offers a processing method capable of automatically recognizing a high number of homologous points among overlapping images and, consequently, generating dense point clouds (PC). The following camera internal orientation (IO) parameters were considered as additional unknowns during bundle adjustment and their estimates generated to refine solution [83]: (Cx, Cy) = principal point offset; (K1,K2,K3,K4) = radial distortion coefficients; (B1,B2) = affinity and skew (non-orthogonality) transformation coefficients.; (P1, P2) = tangential distortion coefficients. Previous experience using Agisoft showed that the numerical solution of the adjustment is often reached when requiring IO parameters' estimation, absorbing most of the uncertainty in the focal length (f) estimate; this solution proved to generate a significant variation in the scale of measures, making deductions (mainly vertical) unreliable and significantly wrong.

Some further discussion would be needed to completely clarify under which conditions these types of unfavorable solution can be generated by SfM-MVS. For example, it is well-known that this is more probable where scene topography is flat; but similarly, it can occur even in mountain areas when GCPs spatial distribution is not proper (i.e., they are located in very similar height conditions). This situation cannot be excluded when GCPs are derived from existing maps/orthoimages that, obviously, limit the possibility of locating GCPs depending on local territorial elements. Given the operational scenario we are discussing, where users are supposed to be weakly conscious of DAP theoretical issues, we suggest operating fixing the focal length to its nominal value when operating image bundle adjustment with IO estimation. Accordingly, for the example we are referring to, the focal length was not included among the unknowns and was fixed to its nominal value (50 mm). IO parameters are reported in Table 2 together with resection errors. Using leave-one-out procedure in Agisoft Metashape involving GCP coordinates, horizontal and vertical accuracies (MAE_H and $MAE_{V,}$ respectively) were computed. Adjustment solution was achieved using 161,000 Tie Points that Agisoft Metashape located using a medium strategy.

Table 2. Camera internal parameters estimated by Agisoft Metashape. Cx, Cy—principal point coordinates, K1, K2, K3, K4—radial distortion coefficients, P1, P2, P3, P4—tangential distortion coefficients, B1, B2—affinity and non-orthogonality (skew) coefficients. Focal length was fixed at its nominal value (0.05 m). In the last two lines, the table also reports horizontal and vertical accuracy as computed by leave-one-out from GCPs after adjustment.

Interior Orientation Parameters	Value (# Pixels)
Cx	59.271
Cy	−10.076
K1	−0.041
K2	0.041
K3	−0.032
K4	0.025
B1	−0.840
B2	−0.579
P1	0.000
P2	0.000
P3	0.000
P4	0.000
Horizontal Accuracy (MAE_H, m)	0.7
Vertical Accuracy (MAE_V, m)	1.8

Actual vertical uncertainty (σ_z = 1.80 m) appeared to be significantly higher than the theoretical (σ_z = 0.50 m). This probably depends on positional errors affecting cartographic data used for GCP acquisition. In these conditions, the former (1.80 m) is the one that has to be taken into consideration for measuring purposes; in spite of this it, however, proved to be comparable (even better) than the one affecting ordinary ground-based tree height surveys [66].

3.3. Post-flight Validation of Acquisition

The estimates of EO parameters from image block adjustment were analyzed to test consistency of flight with expected requirements. Flight plan variables were computed back to compare their expected value with that actually achieved during the flight. The analysis was performed by a self-developed routine implemented in the Interactive Data Language vs. 8.0 programming language, taking care of the varying topography in the area. Consequently, most parameters are reported as their minimum and maximum values depending on AGL height within the block as deduced by DTM. Results of tests are reported in Table 3.

Table 3. A posteriori computed values of the main flight parameters. Values are obtained with reference to the extreme geometric situations found when exploring and processing external orientation parameters as estimated by Agisoft Metashape for both blocks.

Flight Parameters	Value
Min Terrain Elevation (m a.s.l.)	450
Max Terrain Elevation (m a.s.l.)	2150
Max AGL altitude (m)	2259
Min AGL altitude (m)	559
Average AGL altitude (m)	1700
Image scale (max)	11,178
Image scale (min)	45,178
GSD (max, m)	0.17
GSD (min, m)	0.04
Along track footprint (max, m)	1809
Along track footprint (min, m)	448
Across track footprint (max, m)	2413
Across track footprint (min, m)	597
Forward overlap (max, %)	89
Forward overlap (min, %)	55
Side overlap (max, %)	76
Side overlap (min, %)	6
Baseline (median value, m)	200
Flight Line distance (m)	558
B/H ratio	0.12
Nominal Vertical accuracy (min, m)	0.96
Nominal Vertical accuracy (max, m)	0.06

According to Tables 2 and 3, most of the programmed parameters for Digisky were satisfied, making the data provided consistent with expected requirements.

3.4. Image Intersection

A dense point cloud was generated from the adjusted block by automatic intersection following MVS (Multiple View Stereo) procedures. It is worth remembering that, in forestry, PCs are at the basis of the effective description of tree structural characteristics and that points belonging to the cloud are 3D spatially positioned in the same reference system of GCPs. A critical issue to deal with is the final point density (pt/m^2), that, for forestry purposes, is expected to be higher than some points per m^2 (possibly > 10) [84,85]. Image intersection was achieved using a medium strategy. Totally, 579,788,251 points were measured during intersection to generate the correspondent Dense Cloud (DC). DC was therefore exported in LAS format and analysed by LASTools (vs. 210,720) to get an estimate of point density. This proved to be 5 pt/m^2 in the area on average. If we compare this value with the estimated average pixel size of images (GSD = (0.17 + 0.04)/2 = 0.11, see Table 2), the intersection efficiency (number of points/number of pixels per m^2) can be computed. Since 1 m^2 contains about 82 image pixels and five points of DC, the efficiency can be estimated as 5/82 = 0.06 (6%). This means that, under the tested conditions and with reference to the adopted strategies in Agisoft Metashape, the block was able to generate, averagely, one point every 17 image pixels, corresponding to about a 4 $\times$ 4 pixels window. Consequently, one can assume that a proper GSD for the DSM that can be generated through DC regularization is 0.11 $\times$ 4 = 0.44 m. According to Equation (3), the minimum height difference (Δh) that can be detected over a tree crown having an average slope of 35° from a DSM having a GSDD = 0.44 m is therefore 0.31 m. Again, the most limiting factor appears to be the actual vertical accuracy (1.8 m) as estimated by leave-one-out during image block bundle adjustment.

3.5. Comparing DAP and Ground Based Surveys: Economic Issues in the CFC Area

In order to economically compare ground- and DAP-based surveys the expected number of plots that a given forest stand requires has to be computed, as the most impacting factor from the economic point of view. This can be estimated by Equation (4). As far as the area managed by CFC is concerned, the following values were adopted: ε% = 10% and t = 1.96 (i.e., 95% confidence level). CV% values for tree basal area were obtained from the Piemonte Regional Forestry technical guidelines [86]. CV% of basal area was selected since it is well known to be correlated to biomass, while it is not affected by the forest volume estimation method. Results are listed in Table 4 for each of the forest types present in the entire area that CFC is managing.

Table 4. Forest types in AOI as mapped by [62].

Forest Type	Area (ha)	CV%	*n*
Turkey oak	62.5	46	81
European alder	25.8	51	100
Maple and Ash	34.9	54	112
Pioneer Stands	1251.0	54	112
Chestnut	508.0	45	78
Beech	28.6	42	68
Larch and Stone pine	30.8	52	104
Downy oak	44.0	52	104
Forest plantations	113.1	50	96
Black locust	43.0	56	120
Total	2142.0		975

Table 4 shows that a total of 975 sample plots is the representative sample size to properly survey the dendro-metric features of the area for FI purposes. According to the Italian Agronomist professional price list [87], the hourly forest practitioner cost is about €56·h^{-1}. A practitioner is expected to be able to survey two plots in one hour (circular plots with 20 m radius). In AOI, according to Table 4, 10 forestry types are present; consequently, the total cost for ground surveys can be estimated at about €27,300.

Conversely, the cost associated with a photogrammetric aerial survey can be estimated as €5 ha^{-1} under the condition that a 1 h flight has to be minimally guaranteed. This can be approximately thought to correspond to about 1000 ha of imaged forest. All these data were supplied by Digisky, according to their ordinary working mode. Given the total size of the area managed by CFC (2142 ha), the cost associated with the acquisition phase can be estimated as 5 × 2142 = €10,710. Additionally, after the flight, a complete photogrammetric workflow for image orientation and dense cloud, DSM and ortho-mosaic generation is needed, together with post-processing steps (segmentation or local maxima) aimed at retrieving dendro-metric parameters from CHM. These, necessarily, introduce additional costs. To obtain an estimate of costs related to computational times associated with image processing, the following considerations were made. Initially, we recorded times required by the steps of the photogrammetric workflow, as manageable in Agisoft Metashape, through a computer equipped with an Intel® Core (TM) i9-990 K CPU @ 3.6 GHz and 64 Gb RAM. It was found that, for the processed block, 3 h were required for data preparation, GCP measurement, bundle refinement and leave-one-out implementation. This estimate does not include machine time. A skilled technician able to consciously manage this step was assumed to cost €56 h^{-1}. Assuming that four image blocks (according to Digisky) are needed to completely describe CFC managed forests, a total cost of about 3 × 4 × 56 = €670 can be estimated for this step. Since DAP also requires some ground surveys to calibrate allometric models, three ground plots per hectare were assumed to be enough for each forest type (10 in the area). Consequently, with reference to the above-mentioned forestry practitioner (hourly cost estimated as €56 h^{-1}) able to survey two plots per hour, the cost associated with this step can be estimated as (10 × 3)/2 × 56 = €840.

Concluding, the total cost associated with this DAP-based EFI can be estimated as 10,710 + 670 + 840 = €12,220. This makes it possible to state that DAP-based EFI determines a potential saving of about 66% of costs with some further benefits such as measurement repeatability and homogeneity and guaranteeing a more complete (wall-to-wall) knowledge of the area. In fact it must be considered that, for this case study, only 1200 $m^2 \cdot ha^{-1}$, corresponding to about the 12% of the PFA, were surveyed directly on the field. Future developments will be expected to assess and compare FI precision, in terms of dendrometric survey accuracies, once both ground-based FI and DAP-based FI are available.

Despite this cost-saving, DAP-derived estimates cannot directly be compared to ground ones. In fact, using ordinary ground-based sampling, much more information can be collected (e.g., species composition, growth conditions, stand quality, forest status/health). This lack could only be filled by integrating ground and remotely sensed measures. Nevertheless, DAP-based EFI allows retrieval of forest measures that are suddenly available to the field surveyors before ground sampling. Therefore, the a priori knowledge of the most common dendro-metric features (and their spatial variability) allows optimization of the always expensive but mandatory field surveys by planning a stratified or more focused ground survey.

4. Conclusions

In this work, a critical summary and some discussion were offered about the requirements and potentialities of DAP in forestry, with a specific focus on FPs' redaction. In particular, the authors reviewed approaches and criteria needed to set a proper photogrammetric acquisition able to guarantee adequate image resolution and accuracy. While discussing general issues related to DAP in forestry, they highlighted the most critical issues related to a correct setting of acquisition parameters. They also suggested a new approach, based on silvicultural concerns, to decide the proper GSD of images during flight planning, depending on the expected canopy shape (i.e., monopodial and sympodial forms). The approach showed that conifer stands ordinarily require smaller GSD than broad-leaves to be properly geometrically described by photogrammetric measures. A thorough discussion was also offered about the accuracy of measures and post-flight evaluation of acquisition conditions with special concerns for ordinary procedures for image block orientation. An effort was made to show possible effects of technical choices on forest deductions, making evident that a proper photogrammetric consciousness is mandatory to properly apply DAP in the forest knowledge context.

In order to exemplify all these concerns a paradigmatic case study was presented dealing with forests managed by CFC in Piemonte (NW Italy). A comparison was made between traditional FI based deductions (survey types, timing and related costs) and those from DAP in the EFI framework. It was demonstrated that, given the reduced positional accuracy requirements of forestry measures, some simplifications can be introduced in the photogrammetric workflow to reduce costs and speed up the process. From this point of view, the most effective issue that was discussed was that related to GCP acquisition. They were, in fact, derived from proper existing official geographical data, making it possible to avoid expensive and time-consuming ground surveys. The properness of this choice related to accuracy instances was demonstrated with reference to expected quality of forest measures. Additionally, it was shown how, while committing image acquisitions to external companies, it is possible to a posteriori test the properness of the acquired image blocks and their consistency with programmed flight parameters. This test entirely relied on the analysis of the estimated values of image EO parameters after bundle adjustment. A preliminary cost analysis was also made comparing traditional FI, based on a stratified sampling strategy, and EFI, based on DAP. Results made possible an estimated cost saving of about 66% by using EFI in place of FI. It was also found that, while during FI only a few hectares can be directly surveyed (about 1200 $m^2 \cdot ha^{-1}$), during EFI a direct photogrammetrically based survey is possible for the whole area, highly improving the overall knowledge of the forest stands. In spite of this, DAP is showing great potential in the technology transfer frame-work, even if some further developments should abandon proof-of-concept studies and move towards more operative applications of DAP in forestry.

Author Contributions: Conceptualization, E.B.-M.; methodology, E.B.-M. and S.D.P.; software, S.D.P. and E.B.-M.; formal analysis, E.B.-M., S.D.P. and E.J.M.; investigation, E.B.-M. and S.D.P.; data curation, S.D.P., F.S. (Filippo Sarvia), E.J.M., E.B.-M. and F.S. (Filippo Sarvia); writing—original draft preparation, S.D.P., F.S. (Filippo Sarvia) and E.B.-M.; writing—review and editing, F.S. (Filippo Sarvia), S.D.P. and E.B.-M.; visualization, S.D.P., F.S. (Fabio Sussio) and E.B.-M.; supervision, E.B.-M. and P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank Tommaso Orusa for providing precious forest information and Igor Vigna for having provided local information about Canavese Forestry Consortium.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

DAP	Digital Aerial Photogrammetry
GNSS	Global Navigation Satellite System
GIS	Geographical Information System
RS	Remote Sensing
FP	Forest Plan
3D	Three-dimensional
ALS	Airborne Laser Scanning
LiDAR	Light Detection and Ranging
EFI	Enhanced Forest Inventory
PFA	Planned Forest Area
DSM	Digital Surface Model
GSD	Ground Sampling Distance
CHM	Canopy Height Model
DTM	Digital Terrain Model
DBH	Diameter at-Breast Height
WV	Wood Volume
RGB	Red Green Blue
AGL	Above Ground Level
SfM	Structure from Motion
GSD_o	Ground Sampling Distance Ortho-mosaics
GSD_D	Ground Sampling Distance DSM
EO	Exterior Orientation
IMU	Inertial Measurement Unit
RMSE	Root Mean Squared Error
MAE	Mean Absolute Error
CFC	Canavese Forestry Consortium
DISAFA	Department of Agriculture, Forestry and Food Sciences
AOI	Area Of Interest
COD	Crew Operator Deck
GCP	Ground Control Point
AGEA	Italian Agency for Payments in Agriculture
PC	Point Cloud
IO	Internal Orientation
DC	Dense Cloud
MVS	Multiple View Stereo
FI	Forest Inventory

References

1. MIPAAF. *Piano Strategico per l'Innovazione e La Ricerca Nel Settore Agricolo, Alimentare e Forestale 2014–2020*; Ministero Delle Politiche Alimentari, Agricole e Forestali: Roma, Italy, 2015.
2. Momo, E.; De Petris, S.; Sarvia, F.; Borgogno-Mondino, E. Addressing management practices of private forests by remote sensing and open data: A tentative procedure. *Remote Sens. Appl. Soc. Environ.* **2021**, *23*, 100563. [CrossRef]
3. Corona, P.; Chianucci, F.; Quatrini, V.; Civitarese, V.; Clementel, F.; Costa, C.; Floris, A.; Menesatti, P.; Puletti, N.; Sperandio, G.; et al. Precision forestry: Concepts, tools and perspectives in Italy. *For. Riv. Selvic. Ecol. For.* **2017**, *14*, 1–12. [CrossRef]
4. White, J.C.; Coops, N.C.; Wulder, M.A.; Vastaranta, M.; Hilker, T.; Tompalski, P. Remote Sensing Technologies for Enhancing Forest Inventories: A Review. *Can. J. Remote Sens.* **2016**, *42*, 619–641. [CrossRef]
5. Soubry, I.; Doan, T.; Chu, T.; Guo, X. A Systematic Review on the Integration of Remote Sensing and GIS to Forest and Grassland Ecosystem Health Attributes, Indicators, and Measures. *Remote Sens.* **2021**, *13*, 3262. [CrossRef]
6. Baskent, E.Z.; Keleş, S. Spatial forest planning: A review. *Ecol. Model.* **2005**, *188*, 145–173. [CrossRef]
7. Grigolato, S.; Mologni, O.; Cavalli, R. GIS Applications in Forest Operations and Road Network Planning: An Overview over the Last Two Decades. *Croat. J. For. Eng. J. Theory Appl. For. Eng.* **2017**, *38*, 175–186.
8. Brown, G.G.; Reed, P. Public Participation GIS: A New Method for Use in National Forest Planning. *For. Sci.* **2009**, *55*, 166–182.
9. Abdi, E.; Majnounian, B.; Darvishsefat, A.; Mashayekhi, Z.; Sessions, J. A GIS-MCE based model for forest road planning. *J. For. Sci.* **2009**, *55*, 171–176. [CrossRef]
10. Schaller, J. GIS application in environmental planning and assessment. *Comput. Environ. Urban Syst.* **1992**, *16*, 337–353. [CrossRef]
11. Campo, A.G.D. GIS in Environmental Assessment: A Review of Current Issues and Future Needs. *Prog. Environ. Assess. Policy Manag. Theory Pract.* **2016**, 121–143. [CrossRef]
12. Goodbody, T.R.H.; Coops, N.C.; White, J.C. Digital Aerial Photogrammetry for Updating Area-Based Forest Inventories: A Review of Opportunities, Challenges, and Future Directions. *Curr. For. Rep.* **2019**, *5*, 55–75. [CrossRef]
13. Balenović, I.; Seletković, A.; Pernar, R.; Marjanović, H.; Vuletic, D.; Paladinić, E.; Kolic, J.; Benko, M. Digital Photogrammetry—State of the Art and Potential for Application in Forest Management in Croatia. *South-east Eur. For.* **2011**, *2*, 81–93. [CrossRef]
14. De Petris, S.; Berretti, R.; Sarvia, F.; Mondino, E.C.B. Precision arboriculture: A new approach to tree risk management based on geomatics tools. *Remote Sens.* **2019**, *11149*, 111491G. [CrossRef]
15. De Petris, S.; Sarvia, F.; Borgogno-Mondino, E. RPAS-based photogrammetry to support tree stability assessment: Longing for precision arboriculture. *Urban For. Urban Green.* **2020**, *55*, 126862. [CrossRef]
16. De Petris, S.; Momo, E.J.; Sarvia, F.; Borgogno-Mondino, E. Multitemporal dual-pol Sentinel-1 data to support monitoring of forest post-fire dynamics. *Geocarto Int.* **2022**, 1–22. [CrossRef]
17. Mondino, E.B.; Gajetti, M. Preliminary considerations about costs and potential market of remote sensing from UAV in the Italian viticulture context. *Eur. J. Remote Sens.* **2017**, *50*, 310–319. [CrossRef]
18. Mondino, E.B. Remote Sensing from RPAS in Agriculture: An Overview of Expectations and Unanswered Questions. *Remote Sens.* **2017**, *49*, 483–492. [CrossRef]
19. McRoberts, R.E.; Tomppo, E.O. Remote sensing support for national forest inventories. *Remote Sens. Environ.* **2007**, *110*, 412–419. [CrossRef]
20. Wulder, M. Optical Remote-Sensing Techniques for the Assessment of Forest Inventory and Biophysical Parameters. *Prog. Phys. Geogr.* **1998**, *22*, 449–476. [CrossRef]
21. Korpela, I. Individual tree measurements by means of digital aerial photogrammetry. *Silva Fenn. Monogr.* **2004**, *2004*. [CrossRef]
22. Lim, K.S.; Treitz, P.M. Estimation of above ground forest biomass from airborne discrete return laser scanner data using canopy-based quantile estimators. *Scand. J. For. Res.* **2004**, *19*, 558–570. [CrossRef]
23. Næsset, E. Airborne Laser Scanning as a Method in Operational Forest Inventory: Status of Accuracy Assessments Accomplished in Scandinavia. *Scand. J. For. Res.* **2007**, *22*, 433–442. [CrossRef]
24. Ginzler, C.; Hobi, M.L. Countrywide Stereo-Image Matching for Updating Digital Surface Models in the Framework of the Swiss National Forest Inventory. *Remote Sens.* **2015**, *7*, 4343–4370. [CrossRef]
25. Crawford, B.; Kasmidi, M.; Korompis, F.; Pollnac, R.B. Factors Influencing Progress in Establishing Community-Based Marine Protected Areas in Indonesia. *Coast. Manag.* **2006**, *34*, 39–64. [CrossRef]
26. Borgogno-Mondino, E.; Fissore, V.; Falkowski, M.J.; Palik, B. How far can we trust forestry estimates from low-density LiDAR acquisitions? The Cutfoot Sioux experimental forest (MN, USA) case study. *Int. J. Remote Sens.* **2020**, *41*, 4551–4569. [CrossRef]
27. Kangas, A.; Gobakken, T.; Puliti, S.; Hauglin, M.; Naesset, E. Value of airborne laser scanning and digital aerial photogrammetry data in forest decision making. *Silva Fenn.* **2018**, *52*, 19. [CrossRef]
28. Koch, B. Remote Sensing Supporting National Forest Inventories NFA. In *FAO Knowledge Reference for National Forest Assessments*; FAO: Rome, Italy, 2015; pp. 77–92.
29. Leberl, F.; Irschara, A.; Pock, T.; Meixner, P.; Gruber, M.; Scholz, S.; Wiechert, A. Point Clouds. *Photogramm. Eng. Remote Sens.* **2010**, *76*, 1123–1134. [CrossRef]
30. White, J.C.; Wulder, M.A.; Vastaranta, M.; Coops, N.C.; Pitt, D.; Woods, M. The Utility of Image-Based Point Clouds for Forest Inventory: A Comparison with Airborne Laser Scanning. *Forests* **2013**, *4*, 518–536. [CrossRef]
31. Fonstad, M.A.; Dietrich, J.T.; Courville, B.C.; Jensen, J.L.; Carbonneau, P.E. Topographic structure from motion: A new development in photogrammetric measurement. *Earth Surf. Process. Landforms* **2012**, *38*, 421–430. [CrossRef]

32. Giannetti, F.; Chirici, G.; Gobakken, T.; Næsset, E.; Travaglini, D.; Puliti, S. A new approach with DTM-independent metrics for forest growing stock prediction using UAV photogrammetric data. *Remote Sens. Environ.* **2018**, *213*, 195–205. [CrossRef]
33. Mikita, T.; Janata, P.; Surový, P. Forest Stand Inventory Based on Combined Aerial and Terrestrial Close-Range Photogrammetry. *Forests* **2016**, *7*, 165. [CrossRef]
34. Piermattei, L.; Karel, W.; Wang, D.; Wieser, M.; Mokroš, M.; Surovỳ, P.; Koreň, M.; Tomaštík, J.; Pfeifer, N.; Hollaus, M. Terrestrial Structure from Motion Photogrammetry for Deriving Forest Inventory Data. *Remote Sens.* **2019**, *11*, 950. [CrossRef]
35. Mokroš, M.; Vỳbošt'ok, J.; Tomaštík, J.; Grznárová, A.; Valent, P.; Slavík, M.; Merganič, J. High Precision Individual Tree Diameter and Perimeter Estimation from Close-Range Photogrammetry. *Forests* **2018**, *9*, 696. [CrossRef]
36. Dash, J.P.; Watt, M.S.; Pearse, G.D.; Heaphy, M.; Dungey, H.S. Assessing very high resolution UAV imagery for monitoring forest health during a simulated disease outbreak. *ISPRS J. Photogramm. Remote Sens.* **2017**, *131*, 1–14. [CrossRef]
37. Michez, A.; Piégay, H.; Lisein, J.; Claessens, H.; Lejeune, P. Classification of riparian forest species and health condition using multi-temporal and hyperspatial imagery from unmanned aerial system. *Environ. Monit. Assess.* **2016**, *188*, 146. [CrossRef]
38. Lehmann, J.R.K.; Nieberding, F.; Prinz, T.; Knoth, C. Analysis of Unmanned Aerial System-Based CIR Images in Forestry—A New Perspective to Monitor Pest Infestation Levels. *Forests* **2015**, *6*, 594–612. [CrossRef]
39. Alonzo, M.; Andersen, H.-E.; Morton, D.C.; Cook, B.D. Quantifying Boreal Forest Structure and Composition Using UAV Structure from Motion. *Forests* **2018**, *9*, 119. [CrossRef]
40. Saarinen, N.; Vastaranta, M.; Näsi, R.; Rosnell, T.; Hakala, T.; Honkavaara, E.; Wulder, M.A.; Luoma, V.; Tommaselli, A.M.; Imai, N.N.; et al. Assessing Biodiversity in Boreal Forests with UAV-Based Photogrammetric Point Clouds and Hyperspectral Imaging. *Remote Sens.* **2018**, *10*, 338. [CrossRef]
41. Smith, M.; Carrivick, J.; Quincey, D. Structure from Motion Photogrammetry in Physical Geography. *Prog. Phys. Geogr.* **2016**, *40*, 247–275. [CrossRef]
42. Bemis, S.P.; Micklethwaite, S.; Turner, D.; James, M.R.; Akciz, S.; Thiele, S.T.; Bangash, H.A. Ground-Based and UAV-Based Photogrammetry: A Multi-Scale, High-Resolution Mapping Tool for Structural Geology and Paleoseismology. *J. Struct. Geol.* **2014**, *69*, 163–178. [CrossRef]
43. Lisein, J.; Pierrot-Deseilligny, M.; Bonnet, S.; Lejeune, P. A Photogrammetric Workflow for the Creation of a Forest Canopy Height Model from Small Unmanned Aerial System Imagery. *Forests* **2013**, *4*, 922–944. [CrossRef]
44. Pitkänen, J.; Maltamo, M.; Hyyppä, J.; Yu, X. Adaptive Methods for Individual Tree Detection on Airborne Laser Based Canopy Height Model. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2004**, *36*, 187–191.
45. Simard, M.; Pinto, N.; Fisher, J.B.; Baccini, A. Mapping Forest Canopy Height Globally with Spaceborne Lidar. *J. Geophys. Res. Biogeosciences* **2011**, *116*. [CrossRef]
46. Mielcarek, M.; Stereńczak, K.; Khosravipour, A. Testing and Evaluating Different LiDAR-Derived Canopy Height Model Generation Methods for Tree Height Estimation. *Int. J. Appl. Earth Obs. Geoinf.* **2018**, *71*, 132–143. [CrossRef]
47. Olaya, V.; Conrad, O. Geomorphometry in SAGA. *Dev. Soil Sci.* **2009**, *33*, 293–308.
48. Hyyppa, J.; Kelle, O.; Lehikoinen, M.; Inkinen, M. A Segmentation-Based Method to Retrieve Stem Volume Estimates from 3-D Tree Height Models Produced by Laser Scanners. *IEEE Trans. Geosci. Remote Sens.* **2001**, *39*, 969–975. [CrossRef]
49. Lingua, A.; Mondino, E.B. High-Resolution Satellite Imagery Orthoprojection Using Dense DEM. In Proceedings of the Image and Signal Processing for Remote Sensing VIII., International Society for Optics and Photonics. Bellingham, WA, USA, 13 March 2003; Volume 4885, pp. 433–443.
50. West, P.W.; West, P.W. *Tree and Forest Measurement*; Springer: Berlin/Heidelberg, Germany, 2009.
51. van Laar, A.; Akça, A. Forest Mensuration. In *Managing Forest Ecosystems*, 2nd ed.; completely rev. and supplemented; Springer: Dordrecht, The Netherlands, 2007; ISBN 978-1-4020-5990-2.
52. Niklas, K.J. *Plant Allometry: The Scaling of Form and Process*; University of Chicago Press: Chicago, IL, USA, 1994.
53. De Petris, S.; Momo, E.J.; Borgogno-Mondino, E. Supporting Assessment of Forest Burned Areas by Aerial Photogrammetry: The Susa Valley (NW Italy) Fires of Autumn 2017. In Proceedings of the International Conference on Computational Science and Its Applications; On-line. Springer: Berlin/Heidelberg, Germany, 2020; pp. 829–844.
54. De Petris, S.; Berretti, R.; Sarvia, F.; Borgogno Mondino, E. When a Definition Makes the Difference: Operative Issues about Tree Height Measures from RPAS-Derived CHMs. *iForest-Biogeosciences For.* **2020**, *13*, 404. [CrossRef]
55. Hu, X.; Li, D. Research on a Single-Tree Point Cloud Segmentation Method Based on Uav Tilt Photography and Deep Learning Algorithm. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2020**, *13*, 4111–4120.
56. Manconi, A.; Ziegler, M.; Blöchliger, T.; Wolter, A. Optimization of Unmanned Aerial Vehicles Flight Planning in Steep Terrains. *Int. J. Remote Sens.* **2019**, *40*, 2483–2492. [CrossRef]
57. Stöcker, C.; Nex, F.; Koeva, M.; Gerke, M. High-Quality Uav-Based Orthophotos for Cadastral Mapping: Guidance for Optimal Flight Configurations. *Remote Sens.* **2020**, *12*, 3625. [CrossRef]
58. Kraus, K. Photogrammetry. In *Photogrammetry*; de Gruyter: Berlin, Germany, 2011.
59. Capolupo, A.; Saponaro, M.; Borgogno Mondino, E.; Tarantino, E. Combining Interior Orientation Variables to Predict the Accuracy of Rpas–Sfm 3D Models. *Remote Sens.* **2020**, *12*, 2674. [CrossRef]
60. Borgogno Mondino, E. Multi-Temporal Image Co-Registration Improvement for a Better Representation and Quantification of Risky Situations: The Belvedere Glacier Case Study. *Geomat. Nat. Hazards Risk* **2015**, *6*, 362–378. [CrossRef]

61. Fissore, V.; Motta, R.; Palik, B.; Mondino, E.B. The Role of Spatial Data and Geomatic Approaches in Treeline Mapping: A Review of Methods and Limitations. *Eur. J. Remote Sens.* **2015**, *48*, 777–792. [CrossRef]
62. Larsen, D.R.; Hann, D.W.; Stearns-Smith, S.C. Accuracy and Precision of the Tangent Method of Measuring Tree Height. *West. J. Appl. For.* **1987**, *2*, 26–28. [CrossRef]
63. Hunt, E.R., Jr.; Daughtry, C.S. What Good Are Unmanned Aircraft Systems for Agricultural Remote Sensing and Precision Agriculture? *Int. J. Remote Sens.* **2018**, *39*, 5345–5376. [CrossRef]
64. Kohyama, T. Significance of Architecture and Allometry in Saplings. *Funct. Ecol.* **1987**, 399–404. [CrossRef]
65. Sakai, S. Sympodial and Monopodial Branching in Acer (Aceraceae): Evolutionary Trend and Ecological Implications. *Plant Syst. Evol.* **1990**, *171*, 187–197. [CrossRef]
66. Sakai, S. Sympodial and Monopodial Branching in Acer: Implications for Tree Architecture and Adaptive Significance. *Can. J. Bot.* **1990**, *68*, 1549–1553. [CrossRef]
67. Torresan, C.; Berton, A.; Carotenuto, F.; Di Gennaro, S.F.; Gioli, B.; Matese, A.; Miglietta, F.; Vagnoli, C.; Zaldei, A.; Wallace, L. Forestry Applications of UAVs in Europe: A Review. *Int. J. Remote Sens.* **2017**, *38*, 2427–2447. [CrossRef]
68. Heidarian Dehkordi, R.; Burgeon, V.; Fouche, J.; Placencia Gomez, E.; Cornelis, J.-T.; Nguyen, F.; Denis, A.; Meersmans, J. Using UAV Collected RGB and Multispectral Images to Evaluate Winter Wheat Performance across a Site Characterized by Century-Old Biochar Patches in Belgium. *Remote Sens.* **2020**, *12*, 2504. [CrossRef]
69. Norasma, C.Y.N.; Fadzilah, M.A.; Roslin, N.A.; Zanariah, Z.W.N.; Tarmidi, Z.; Candra, F.S. Unmanned Aerial Vehicle Applications in Agriculture. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Aceh, Indonesia; IOP Publishing: Bristol, UK, 2019; Volume 506, p. 012063.
70. Sarvia, F.; Petris, S.D.; Orusa, T.; Borgogno-Mondino, E. MAIA S2 Versus Sentinel 2: Spectral Issues and Their Effects in the Precision Farming Context. In *Proceedings of the International Conference on Computational Science and Its Applications*; On-line; Springer: Berlin/Heidelberg, Germany, 2021; pp. 63–77.
71. Piero, B.; Borgogno Mondino, E.C.; Tonolo, F.G.; Andrea, L. Orthorectification of High Resolution Satellite Images. ISPRS: Istanbul, Turkey, 2004.
72. Puliti, S.; Ene, L.T.; Gobakken, T.; Næsset, E. Use of Partial-Coverage UAV Data in Sampling for Large Scale Forest Inventories. *Remote Sens. Environ.* **2017**, *194*, 115–126. [CrossRef]
73. Rahlf, J.; Breidenbach, J.; Solberg, S.; Næsset, E.; Astrup, R. Digital Aerial Photogrammetry Can Efficiently Support Large-Area Forest Inventories in Norway. *For. Int. J. For. Res.* **2017**, *90*, 710–718. [CrossRef]
74. Groves, P.D. Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems, [Book Review]. *IEEE Aerosp. Electron. Syst. Mag.* **2015**, *30*, 26–27. [CrossRef]
75. McGlade, J.; Wallace, L.; Reinke, K.; Jones, S. The Potential of Low-Cost 3D Imaging Technologies for Forestry Applications: Setting a Research Agenda for Low-Cost Remote Sensing Inventory Tasks. *Forests* **2022**, *13*, 204. [CrossRef]
76. Brovelli, M.A.; Crespi, M.; Fratarcangeli, F.; Giannone, F.; Realini, E. Accuracy Assessment of High Resolution Satellite Imagery Orientation by Leave-One-out Method. *ISPRS J. Photogramm. Remote Sens.* **2008**, *63*, 427–440. [CrossRef]
77. Chai, T.; Draxler, R.R. Root Mean Square Error (RMSE) or Mean Absolute Error (MAE)?–Arguments against Avoiding RMSE in the Literature. *Geosci. Model Dev.* **2014**, *7*, 1247–1250. [CrossRef]
78. Ajayi, O.G.; Salubi, A.A.; Angbas, A.F.; Odigure, M.G. Generation of Accurate Digital Elevation Models from UAV Acquired Low Percentage Overlapping Images. *Int. J. Remote Sens.* **2017**, *38*, 3113–3134. [CrossRef]
79. Eid, T. Models for Prediction of Basal Area Mean Diameter and Number of Trees for Forest Stands in South-Eastern Norway. *Scand. J. For. Res.* **2001**, *16*, 467–479. [CrossRef]
80. Rodriguez, E.; Morris, C.S.; Belz, J.E. A Global Assessment of the SRTM Performance. *Photogramm. Eng. Remote Sens.* **2006**, *72*, 249–260. [CrossRef]
81. Kraus, K. Photogrammetry: Geometry from Images and Laser Scans. Walter de Gruyter: Berlin, Germany, 2007; Volume 1.
82. Hasegawa, H.; Matsuo, K.; Koarai, M.; Watanabe, N.; Masaharu, H.; Fukushima, Y. DEM Accuracy and the Base to Height (B/H) Ratio of Stereo Images. *Int. Arch. Photogramm. Remote Sens.* **2000**, *33*, 356–359.
83. *Agisoft Metashape User Manual—Professional Edition*, Version 1.7. 2021; User manual.
84. Wallace, L.; Lucieer, A.; Watson, C.; Turner, D. Development of a UAV-LiDAR System with Application to Forest Inventory. *Remote Sens.* **2012**, *4*, 1519–1543. [CrossRef]
85. St-Onge, B.; Audet, F.-A.; Bégin, J. Characterizing the Height Structure and Composition of a Boreal Forest Using an Individual Tree Crown Approach Applied to Photogrammetric Point Clouds. *Forests* **2015**, *6*, 3899–3922. [CrossRef]
86. IPLA INDICAZIONI TECNICO-METODOLOGICHE PER LA REDAZIONE DEI PIANI FORESTALI AZIENDALI–PFA. 2009. Available online: http://www.regione.piemonte.it/foreste/images/files/pian_gest/dwd/nuova_legge/Indirizzi_PFA_2016_AllegatoA.pdf (accessed on 10 July 2022).
87. D.M. 14 maggio 1991, n. 232 Approvazione Delle Deliberazioni in Data 18 Dicembre 1986 e 12 Settembre 1990 Del Consiglio Nazionale Dei Dottori Agronomi e Forestali Concernenti La Tariffa Professionale Della Categoria. 1991. Available online: http://www.conaf.it/sites/default/files/tariffe_professionali.pdf (accessed on 10 July 2022).