MEASURING FOREST CANOPY HEIGHT USING A COMBINATION OF LIDAR AND AERIAL PHOTOGRAPHY DATA

Benoît A. St-Onge and Nora Achaichia
Department of Geography
Université du Québec à Montréal
Canada
st-onge.benoit@uqam.ca

Commission III, Working Group 3

KEY WORDS: lidar, photogrammetry, forest, aerial photography, canopy, height.

ABSTRACT

It has been demonstrated that the height of forest canopies can be measured with a good accuracy using small footprint lidars. This is essentially accomplished by subtracting the last return altitude (ground) from the corresponding first return altitude (canopy surface). The technique is considered superior to photogrammetric methods mainly because the ground level, which is difficult to see on aerial photos of densely forested areas, can be well identified using small footprint lidars. However, lidar cannot be used to characterized past forest states, while these can be assessed, and photogrammetically measured, in the wealth of historical aerial photographs most developed countries possess. Our goal is to replace the first return lidar data by altitude models derived from aerial photos in order to map forest canopy height changes of the past decades. This paper presents the first methodological steps which consist in comparing canopy heights obtained from lidar data only to a combination of lidar and photogrammetry data. The lidar data was acquired over an area of the boreal forest in Quebec, Canada, in 1998, using Optech's ALTM1020 flying at an altitude of 700 m. Two stereo-pairs of aerial black and white photographs were used: 1) a pair of 1:15,000 photos taken in 1994, and 2) a pair of 1:40,000 photos taken in 1998. A lidar canopy height model (CHM) was created by subtracting ground altitudes from canopy altitudes. Aerial photo altitude models were derived using the image correlation methods of Virtuozo 3.2 software. The ground level altitudinal fit between the aerial photo altitude model and the lidar data was checked on rock outcrops. A photo CHM was created by subtracting the lidar ground altitude model from the aerial photo altitude model. The photo CHM and the lidar CHM show a good degree of correlation.

RÉSUMÉ

Il a été démontré que la hauteur des couverts forestiers peut être mesurée avec une bonne exactitude à l'aide de lidars à petite empreinte. Ceci s'effectue en soustrayant l'altitude des derniers retours (sol nu) des altitudes correspondantes du premier retour (surface du couvert). La technique est considérée comme étant supérieure aux méthodes photogrammétriques en ce qu'elle permet d'identifier correctement le niveau du sol nu alors que ce dernier est rarement visible sur les photos aériennes de zones de forêts fermées. Toutefois, le lidar ne peut être utilisé pour caractériser des états forestiers antérieurs alors que ces derniers peuvent être observés et mesurés photogrammétriquement à partir des nombreuses photos aériennes historiques que possèdent la plupart des pays développés. Notre but est de remplacer les premiers retours du lidar par des modèles d'altitude dérivés de photos aériennes de manière à cartographier l'évolution de la hauteur des couverts forestiers des dernières décennies. Cet article présente les premières étapes méthodologiques qui consistent en une comparaison des hauteurs de couvert dérivées des données lidar de celles produites par la combinaison des données lidar et photographiques. Les données lidar d'une zone de forêt boréale du Québec, Canada, ont été acquises en 1998 à l'aide du capteur ALTM1020 de la compagnie Optech à partir d'une altitude de 700 m. Deux couples stéréo de photo aériennes noir et blanc ont été employées : 1) une paire de photos au 1 :15,000 acquises en 1994 et 2) une paire de photos au 1 :40,000 acquises en 1998. Un modèle lidar de hauteur du couvert (MHC) a été créé en soustrayant les altitudes du sol nu de celles de la végétation. Des modèles d'altitude ont été dérivés des photos en ayant recours à des méthodes de corrélation d'images du logiciel Virtuozo 3.2. L'ajustement altitudinal du niveau sol nu entre les modèles altimétriques photographiques et lidar a été vérifié sur des affleurements rocheux. Un MHC photo a été créé en soustrayant le modèle d'altitude lidar du sol nu du modèle d'altitude de la végétation dérivé des photos. Les corrélations entre les CHM photo et le CHM lidar montrent un bon degré de corrélation.

1 INTRODUCTION

Problem statement

Forest management relies on accurate and up to date spatial information on forest structural characteristics: height, density, timber volume, etc. It is widely recognized that obtaining this information through ground measurements is time consuming and costly. Aerial photo interpretation and photogrammetry have for this reason been widely used. Because the cost of interpreting aerial photos is also high, alternative remote sensing methods were sought. Despite decades of efforts involving the development of new sensors and processing methods, monoscopic remote sensing exploiting the spectral features of images did not succeed in providing reliable measurements of three dimensional forest characteristics at the stand level scale. Tree height in particular is difficult to evaluate from monoscopic vertical images of the forest. Recent progress in three dimensional remote sensing include mainly digital stereophotogrammetry, radar interferometry, and lidar. Sensors producing three dimensional data theoretically provide a better assessment of structural aspects of forests than do monoscopic sensors, an hypothesis that was verified on different occasions (see Hyyppä et al., 2000, and Lefsky et al., 2001 for a comparison).

Digital stereophotogrammetry and radar interferometry can provide maps of the altitude of the canopy surface but usually not accurate canopy height, especially in dense forest environments where the bare earth level remains invisible. It has indeed been know for a long time that "seeing" this level at locations close to a tree is necessary if the height of that tree, i.e. the altitude difference between its top and base, is to be measured (Spurr, 1960; Howard, 1970). Possible confusion of the ground level with the surface of close-by low vegetation can also make height measurements unreliable. Small footprint lidar provides canopy altitude and heights, the latter being the altitude difference between the top of canopy altitude and the bare earth altitude. The very small divergence of laser impulses indeed allow the coherent energy to penetrate dense canopies from place to place. However, lidar surveys are still expensive due to the high number of flight lines needed to cover a given area (due to the lidar narrow swath width), such that forest companies are reluctant to pay for such surveys for large areas, mostly because the huge costs involved will have to be invested at a regular multi-year interval. Also, efficient scanning lidars being fairly recent, the record of past lidar databases is extremely tenuous. Historical monitoring of past forest states using lidar is clearly impossible.

Objectives

To produce the canopy surface and bare earth altitude dual layers from which one can obtain canopy height by simple subtraction, we here investigate the replacement of lidar-produced canopy altitudes by the stereoscopic surface reconstruction from scanned aerial photos. We thus evaluate the potential of combining lidar and digital photogrammetry as a mapping tool of forest structural characteristics, and investigate the effect of air photo scale by testing 1:15,000 and 1:40,000 scales. This relies on the assumption that the ground topography remains essentially unchanged over decades. This study is also a first step to map out the processing steps needed to achieve good results and identify needed improvements before historical studies can be carried out.

2 STUDY AREA

Data and methods have been developed and tested for the *Training and Research Forest of Lake Duparquet* (TRFLD), located in western Quebec, Canada (approx. 48°30' N, 79°22' W). This 80 square km territory is covered by softwood, hardwood and mixed stands typical of the balsam fir-white birch domain of the Canadian Shield. The study area is populated by mature to over mature dense stands, some of which show openings that originated from an spruce budworm outbreak (*Choristoneura fumiferana* [Clem.]), a coniferous defoliator that mostly affects balsam fir, that occurred in the 1980s. The topography is characterized by gentle hills with occasional steeper drops. The altitudes inside the study perimeter vary from 228 m to 335 m above sea level.

3 DATA

Lidar

The lidar survey was carried out on June 28th 1998 using Optech's ALTM 1020 instrument on a Piper Navajo plane flown at 700 m by LaserMap Image Plus. To obtain the desired hit density, two passes were carried out for the first return (canopy) and one for the last return (bare earth). Flight and lidar characteristics are presented in Table 1. Vegetation/ground separation was carried out by the survey provider using Optech's REALM software. No subsequent filtering was done. The average distance between two consequent hits was of 1 m for vegetation, and 3.0 m for the ground. The accuracy is of approximately 20 cm for the altitude values, and of 70 cm for the X,Y values.

Aerial photos

Two stereo-pairs of aerial photos were used in this study. The first was acquired at the scale of 1:15,000 on July 11th 1994 at an above sea level (ASL) altitude of 2600 m. The second was captured at a scale of 1:40,000 on May 8th 1998, i.e. less than two months before the lidar dataset, at altitude of 6400 m ASL. Unfortunately, hardwoods are barely starting to grow leaves at that date produce, which does not provide the best conditions for crown surface reconstruction by image matching. It also important to note that because the study perimeter is close to the 1:15,000 edge, i.e. far from the principal point, tree leaning is quite pronounced. Table 2 presents the detailed characteristics of the photos and figure 2 shows one photo of each pair. Both aerial coverage were produced by contract with the Province of Quebec Ministry of Natural Resources (MRNQ) by Hauts-Monts Inc. independently of this research project's purpose. The two pairs were scanned using a Epson 836XL scanner at a resolution of 1200 dpi. Combined with the two abovementioned photo scales, this yields ground pixel sizes of 0.3 and 0.85 m for 1994 and 1998 respectively. The choice between uniform scanning resolution (which is the case here) and uniform ground pixel size among the photo sets, both of which have advantages as the former "transfers" the original scale of the hardcopy photo to the softcopy while the latter produces a uniform ground pixel size, useful in a comparison, was settled on technical considerations. Optical distortions may indeed occur at resolution greater than 1200 dpi on the particular scanner we used. We hypothesized that the highest resolution allowing optically correct scans should give the best results possible at the image correlation stages on both datasets.

The aerial camera calibration reports were obtained from the MRNQ (see table 2 for details). Unfortunately, an ambiguity in the fiducial marks locations in the 1994 report could not be resolved in time for this study, so the values found in the 1998 report were used temporarily instead. The same aerial camera model had been flown on both years although different units were involved. The consequences of this are discussed in the results section.

Field data

The height of individual trees was measured on the ground using a standard clinometer method. Two measures were taken from different vantage points separated by at least 90 degrees to insure independence between the two measures. Trees for which the two height measures differed by more than 3 meters or by more than 15% were discarded so that errors in comparing lidar-derived heights to actual heights can mostly be attributed to the lidar. These two heights for all well measured trees were later used to assess the accuracy of ground measurements. The study focused on two species: Trembling Aspen (Populus tremuloides [Michx]) and White Spruce (Picea glauca [Moench], Voss.) but some other species were measured. After measurement error filtering, 36 trees remained (12 hardwoods and 24 softwoods). These trees were localized on the lidar dataset by using a combination of high precision GPS and visual analysis of the lidar image and low altitude photography.

4 METHODS

Processing of the lidar data

Generation of the canopy height model The lidar canopy height model (lidar CHM) was obtained by subtracting the interpolated ground-classified hits (lidar ground altitude model, or GAM) from the interpolated vegetation-classified altitudes (lidar canopy altitude model, or lidar CAM – see figure 2a). To create both surfaces, triangulated irregular network (TIN) interpolation of the X,Y,Z lidar hits was converted into a 50 cm pixel size grid.

Validation of lidar canopy heights The lidar CHM gives the interpolated height of all points in the canopy in the form of a regularly spaced grid with a 50 cm pixel size. The height of a tree was defined as the pixel having the highest value in a high-valued pixel cluster corresponding to a crown. This "top pixel" is normally situated near the center of the crown but can sometime be found a few pixels away from the center in the case of large hardwood trees. Linear regression was performed between ground-measured heights and lidar predicted heights (see St-Onge, 1999 for details). The mean of the two height measures done in the field for these trees was regressed against the corresponding height read from the CHM for the 36 trees. The linear model yielded a R^2 of 0.90 (significant at α=0.01). For this reason, we consider lidar derived heights as a surrogate for ground truth in the assessment of the accuracy of the digital stereophotogrammetry results.

Processing of the aerial photo data

Generation of the canopy altitude model The generation of the photo-derived canopy altitude model (photo CAM) was carried out using Virtuozo v. 3.2 from Supresoft. The hierarchical image correlation algorithms employ both statistical correlation and feature base matching to achieve the photo CAM. It is known that, while supervised tree height measurements made using softcopy photogrammetry packages are accurate, current commercial packages are not designed for precise automated crown shape reconstruction (Sheng et al., 2001). This problem lead these authors to develop a crown shape model-based reconstruction method. This method, while very successful in some conditions, is not currently operationally implemented.

The exact values from the camera calibration reports were input in Virtuozo. The relative orientation control points were produced by Virtuozo and were not modified by manual edits. Nine X,Y,Z control points coordinates were read on the lidar data on bare ground (rock outcrops, rocky shores, etc.) and associated with single pixels on the scanned photos. This theoretically constrains the stereo-photo model to fit with the lidar model. The points were spread out as evenly as possible over the studied sector (around the edges, and on the interior). The CAM was created with a 0.5 m pixel size and a 0.1 m Z precision and transferred from the Virtuozo format to a binary floating point number grid format for the further processing steps.

Generation of the aerial photo canopy height models The aerial photo CHM was generated by subtracting the lidar GAM from the photo CAM of each stereo-pair. The result shows the variations of canopy height on a 0.5 m pixel basis according to the surface reconstructed from the photos.

5 RESULTS AND DISCUSSION

General observations

The CHM created using only lidar, and a combination of the aerial photos and the ground altitude given by lidar are presented in figure 2 b-d (where brightness is proportional to height). We can see that the patterns determined by variation of tree height, crown size and density are very similar from one CHM to an other. It appears that the canopy surface altitude was correctly reconstructed by the image matching process and that the achieved resolution is quite good. We also see that the lidar CHM is quite crisp compared to the 1:15,000 photo CHM and that the definition of the 1:,40,000 photo CHM is still lower than its 1:15,000 counterpart, as could be expected based on the resolution of the original documents.

Close-up observations

Figure 3 shows three close-ups of the CHMs. These reveal that the resolution of the photo CHMs is high enough to resolve tree clusters, and, especially for the 1:15,000 photo CHM, individual trees. We also see that the crown sizes and heights, as perceived via the diameter and brightness of the spots on the lidar and 1:15,000 photo CHMs look very similar, suggesting that these two parameters could be measured on photo CHMs with a certain level of accuracy. A closer look at the lidar and 1:15,000 CHMs reveals some differences. The latter seems “fuller” than the lidar CHM, i.e., the crowns are less defined but more rounded and often wider. We hypothesize that the relatively low lidar hit density (the lidar used for the study was built in 1995; impulse frequencies have since then increased by a factor of 8) results in crowns being hit partially, some smaller crowns being entirely missed. The lidar CHM thus shows “choked” crowns. The 1:15,000 photo CHM was built using high resolution pictures that show the entire crowns (except for the shaded parts). It is therefore not surprising that this photo CHM shows a more closed canopy than the lidar CHM. We can expect a closer resemblance between the lidar CHMs produced by 33KHz lidars and 1:15,000 photo CHMs.

There are also some discrepancies between the summer CHMs (lidar and 1:15,000 photo) and the spring CHM (1:15,000). One is quite obvious on figure 3 (middle row) in the dense patch of forest at the extreme left of each CHM. This patch is completely closed in the summer CHM but has important gaps in the spring CHM. The most plausible explanation for that is that the almost leafless state of hardwood on May 8 1998 (1:40,000) left some foliage free gaps in otherwise closed mixed canopies.

Quantitative comparison: a first assessment

Bare earth level Due to the unresolved ambiguity in the precise locations of the fiducial marks of the 1:15,000 photos, we preferred to postponed a complete quantitative assessment of the canopy height error of the photo CHMs. We did however checked a certain number of pixel values to get a rough idea of the quality of the photo CHMs. A first test consisted in comparing the Z co-registration of the ground level of all CHMs. This test was conducted by first identifying patches where the ground level could be seen. These patches have approximately equal first and last returns lidar altitudes. We compared the lidar ground altitude to the altitudes given by the photo CHMs for the same locations. The altitudes given by the 1:40,000 photo CHM where clearly closer to the (true) lidar altitudes than where the 1:15,000 photo altitudes, which where consistently higher (approx. 8-12 m higher). The altitudes of the 1:40,000 photo altitudes were often within 2-3 m of the lidar altitude on bare ground. We believe that the fact that the fiducial mark locations of the 1998 photos where used for the computation of the interior orientation of the 1994 photos is responsible for these discrepancies. This leads us to think that the co-registration of lidar and photo GAMs can be quite accurate.

Canopy and tree height We define canopy height as the height of the foliage source above ground for any point of the canopy. Tree height is the height of the tree apex (topmost point) above ground. We first assume that in general, the lidar canopy height is quite close to the true height. However, the height value of single trees is often lower in a lidar CHM than in reality because the tree apex, especially of a softwood tree, is quite narrow, and for this reason often missed by lidar hits, thus truncating the tree top. In an earlier study (St-Onge, 1999), we developed a correction equation for this phenomena in the same study region. The tree heights read on the lidar CHM were first corrected using this equation before they were compared with the photo CHM tree heights. In comparing canopy heights between lidar and photo CHMs, one must be sure that the X,Y coregistration of the CHMs is nearly perfect because of the very high spatial frequencies of the height variations. In other words, one should avoid comparing the altitude of the top of a tree on one CHM with the side of that same tree on an other CHM. Because we did not assess the accuracy of the X,Y co-registration, we only compared very broad canopy height variations using a low-medium-high height classification. A more precise study will be carried out later. We found that these broad height variations are very similar on both the lidar and the 1:15,000 CHMs. This corroborates the visually observed high correlation between the brightness levels of these CHMs. The 1:40,000 photo CHM does show height similarities with the lidar CHM, but to a lesser degree. The fact that the leafs were not fully grown on this CHM does not provide us with good comparison conditions, so we did not pursue the comparison further. The major differences between the lidar and 1:15,000 CHMs occurred at gap locations on the lidar side. As said earlier, we believe that most tree crown diameters are shrunk and that some trees are entirely missed because of the relatively low hit density of the ALTM 1020. For this reason, and because of tree leaning on the 1:15,000 photos, there are some cases where there appears to be a tree on the photo CHM and a gap on the lidar CHM. The height discrepancies are of course very high in theses cases.

Conclusion

Even though a detailed quantitative assessment of the accuracy of canopy height models derived from a combination of lidar and photo based surface reconstruction still as to be carried out, the initial observations we made lead us to conclude that:

- lidar altitude models can be co-registered in X,Y,Z to aerial photo derived altitude models,
- general canopy patterns, tree clusters, and on many occasions individual trees are correctly represented in photo CHMs
- photo scale is determinant in the effective resolution of the CHMs
- the height of the canopy and of certain individual trees can be estimated from the photo CHMs, although with a currently unknown level of accuracy.

Its seems reasonable to think at this point that the evolution of the structure of forest canopies over time (height and density increments, gap dynamics, etc.) could be studied using diachronic photo CHMs with a single lidar coverage. These diachronic studies would be possible from past to present states, and, provided the photogrammetrical problems can be solved, the full record of stereo air photos, starting around 1920 for some regions in North America, could be used for this purpose.

Further studies will include full quantitative assessment of canopy height measurements derived from photo CHMs, more precise evaluation of the X,Y,Z co-registration of CHMs, more control over photogrammetrical and image matching parameters, the use off older photos for diachronic studies, and possibly a link to model-based surface reconstruction.

ACKNOWLEDGMENTS

We thank the National Science and Engineering Research Council of Canada, and the Network of Centres of Excellence on Geomatics for Informed Decisions (GEOID). Our gratitude also goes to LaserMap Image Plus (Boisbriand, Québec, Canada) for providing the laser survey at a significantly discounted price.

Date of survey: June 28th 1998
Laser sensor: Optec's ALTM1020
Laser wavelength: 1047 nm
Impulse frequency: 4000 Hz
Scan frequency: 16 Hz
Flight altitude for vegetation and ground: 700 m
Footprint size: 0.19 m
Maximum scan angle from nadir : 10 degrees
Approximate Z accuracy: 20 cm
Approximate X,Y accuracy: 70 cm
Number of passes for first return: 2
Number of passes for last return : 1
Average hit density for vegetation: 1 hit/m^2
Average hit density for ground: 1 hit/2.5 m^2
Vegetation/ground separation : Optec's REALM

Table 1 Lidar characteristics

Nominal scale	1:15,000	1:40,000
Acquisition date	July 11, 1994	May 8, 1998
Camera	Wild RC 10	Wild RC 10
Calibrated focal length	153.234 mm	153.107 mm
Flight altitude over ground level	2600 m asl	6400 m asl
Scanning resolution	1200 dpi	1200 dpi
Nominal ground pixel size	32 cm	85 cm

Table 2 Aerial photos characteristics

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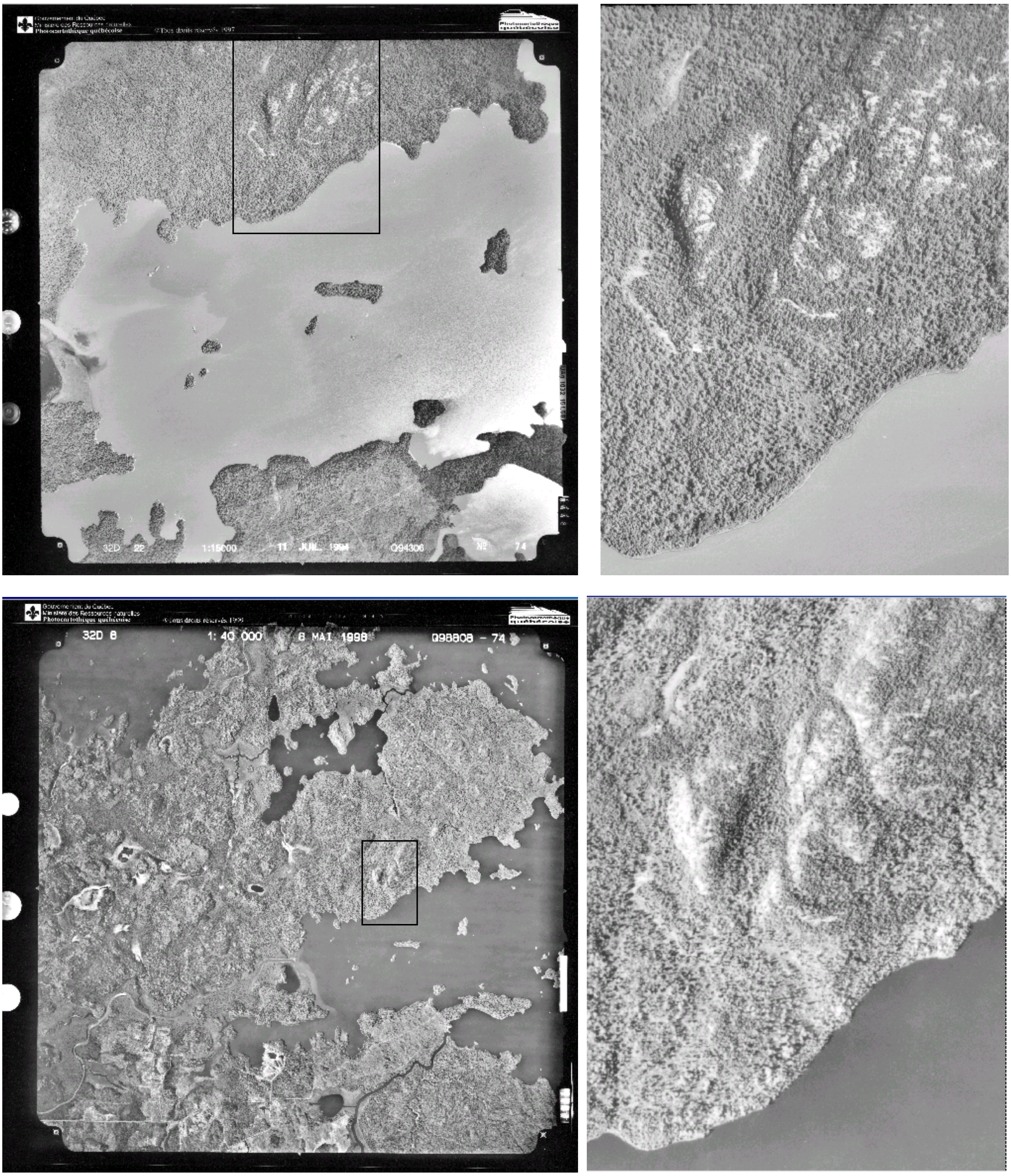

Figure 1 Aerial photos used to create the canopy height models. Top row: one of the 1:15,000 photos with close-up on the study region (rectangle). Bottom row: same for the 1:40,000 photos.

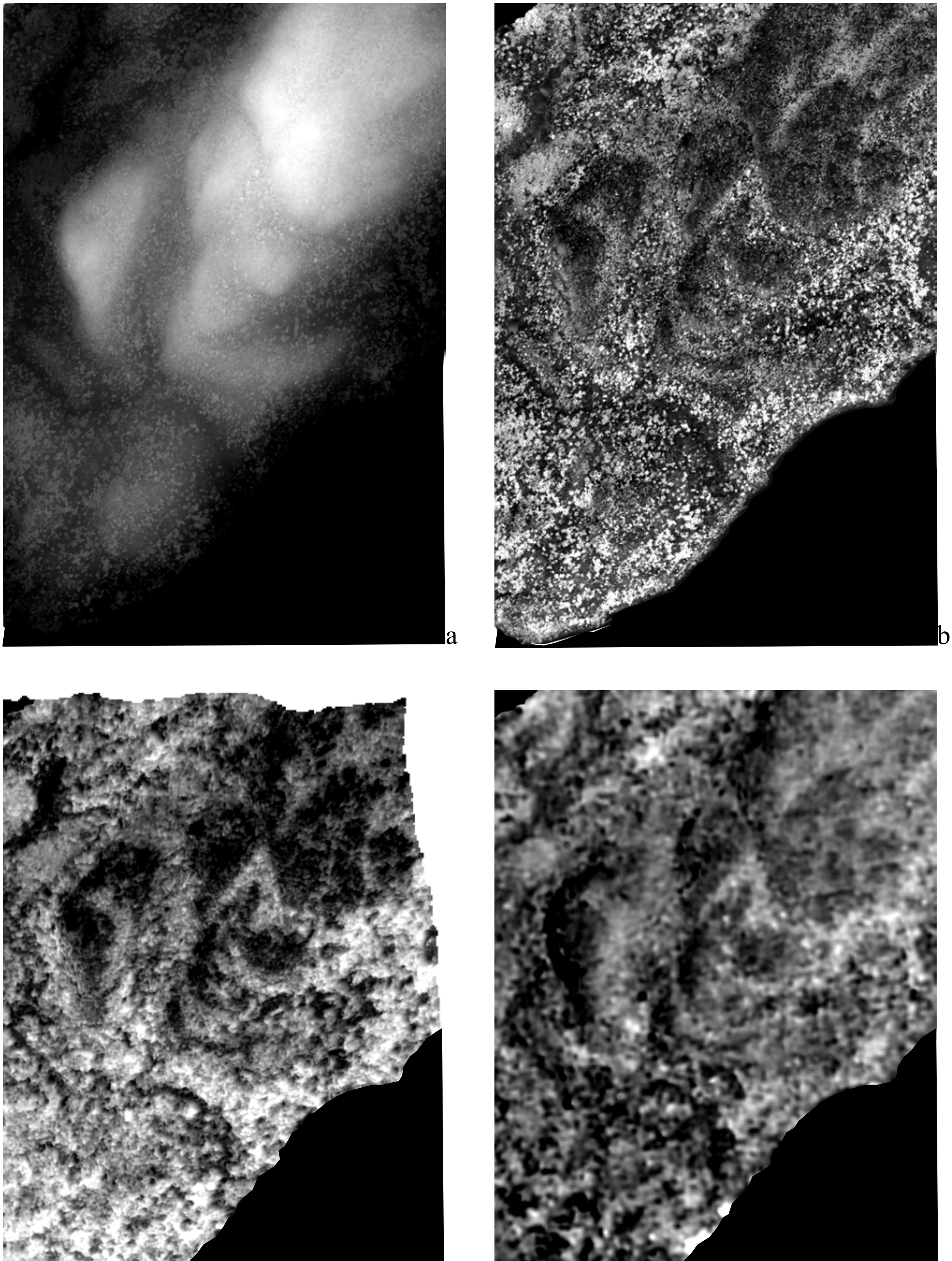

Figure 2 Lidar canopy altitude model (a), lidar CHM (b), 1:15,000 photo CHM (c), 1:40,000 photo CHM (d)

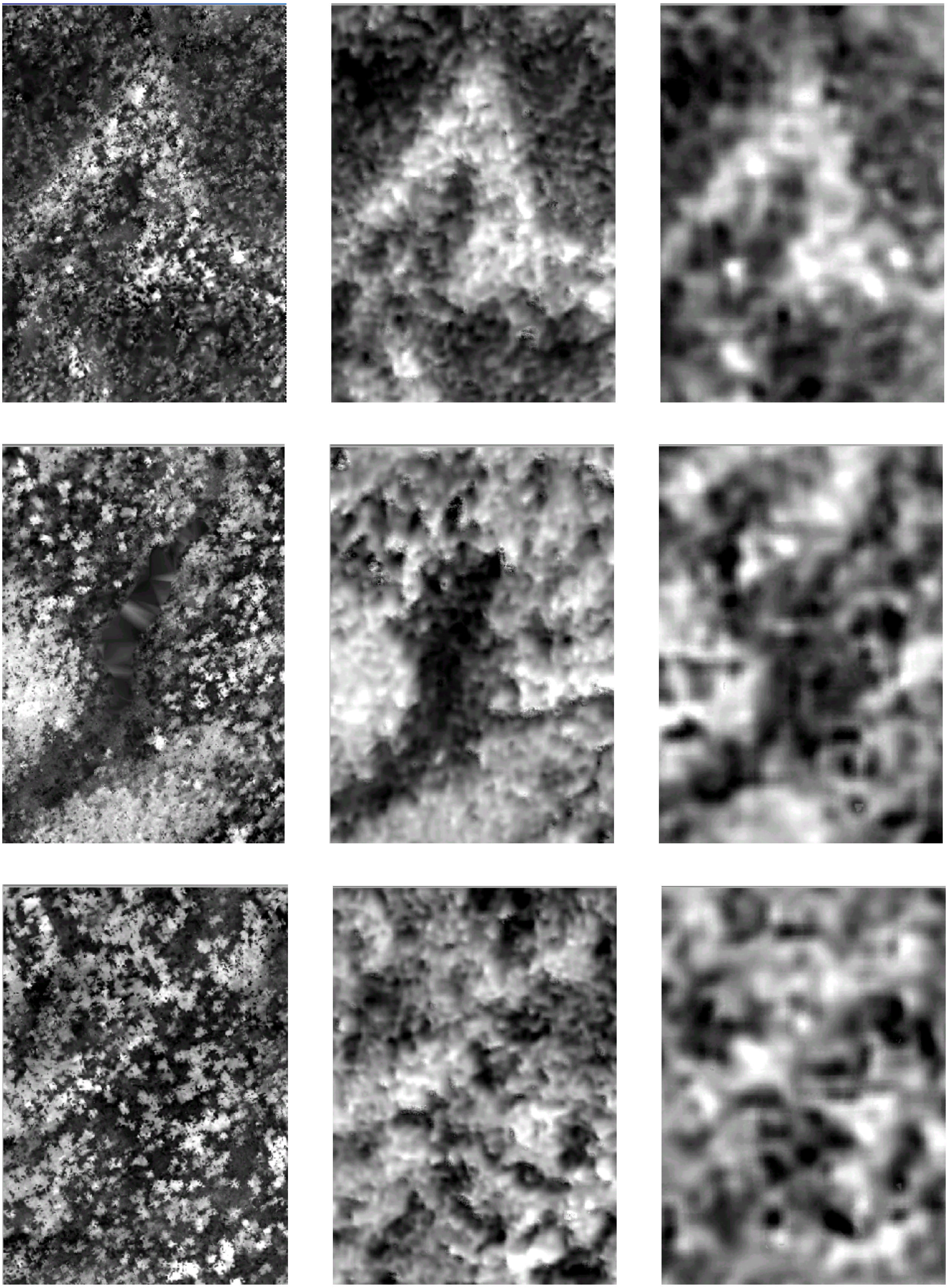

Figure 3 Each row represents a different close-up view. The left column shows the lidar CHM, the middle column the 1:15,000 photo CHM, and the right column the 1:40,000 photo CHM.