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Influence of solar elevation in radiometric and geometric performance of multispectral photogrammetry

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A B S T R A C T

Solar elevation is an important factor in passive, airborne data collection. The minimum solar elevation allowed in missions for topographic mapping is typically 30° from the horizon. A general hypothesis is that the new, high dynamic range, digital large-format photogrammetric sensors allow for high data quality, even with lower solar elevations, which would improve the feasibility and cost-efficiency of photogrammetric technology in various applications. Objectives of this study were to investigate theoretically and empirically the impacts of solar elevation in modern photogrammetric processes. Two cutting-edge aspects of novel photogrammetric technology were considered: point cloud creation by automatic image matching and reflectance calibration of image data. For the empirical study, we used image data collected by a large-format photogrammetric camera, Intergraph DMC, with low (25–28°) and medium (44–48°) solar elevations from 2, 3 and 4 km heights. We did not detect negative influences of decreasing solar elevation during our general evaluations: an analysis of image histograms showed that the ranges of digital numbers could be tuned to similar levels with exposure settings, and evaluations of density and the accuracy of point clouds did not show any reduction of quality. We carried out detailed evaluations in forests, roads and fields. Our results did not indicate deterioration of the quality in sun-illuminated areas with decreasing solar elevation. In shadowed areas, we observed that the variation of image signal was reduced in comparison to sun-illuminated areas and emphasized the issue of complication of reflectance calibration. Artefacts appeared in automatically generated point clouds in areas shadowed by trees, which we observed in flat objects as up to 3 times random height variation and decreased success in measuring the terrain surface. Our results also showed that the overall performance of point cloud generation was high. Typically, point clouds could be derived even from a single stereo model with the point density corresponding to the GSD, but some expected and unexpected failures also appeared. The height accuracy was dependent on the object properties and the intersection geometry; the height accuracy was 0.5–2 times GSD at well defined objects. Our conclusions were that in the future it is of increasing importance to quantify the sensitivity of different methods on the radiometric properties of the image data. It is also important to develop interpretation methods that are not sensitive to shadows, in order to enable optimal use of photogrammetric technology in normal to rapid response applications.

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1. Introduction

Large-format digital photogrammetric imaging provides novel possibilities for the efficient and accurate measurement of geometric and radiometric properties of the environment. The key aspects include high efficiency (large-format sensors, direct georeferencing, efficient aircrafts), high resolution, high geometric accuracy and multiple image overlaps, as well as multispectral, noiseless, high-

dynamic range radiometry and the possibility for reflectance calibration of the image data. It is expected that combining the geometric and radiometric characteristics of photogrammetric imaging with other relevant data sources (especially laser scanner elevation data) will raise the scene interpretation to a new level. For example, photogrammetric multispectral images have been used successfully to improve efficiency in topographic mapping (Zebedin et al., 2006; Le Bris and Boldo, 2008), digital surface model (DSM) generation (DeVenecia et al., 2007; Gülch, 2009; Haala et al., 2010), and forestry applications (St-Onge et al., 2008; Heikkinen et al., in press; Korpela et al., 2011), but thus far the full potential of reflectance/geometric/multiple-multiangular information in photogrammetric data has not been utilized. A recent state-of-the-art review of
photogrammetric production lines of European Mapping Agencies revealed the overall insufficiency of radiometric data (Honkavaara et al., 2009).

One of the key questions in practical applications involves the minimum solar elevation that should be accepted during image collection flights. In photogrammetric mapping projects, the typical demand for the solar elevation is 25–40° from the horizon (Honkavaara et al., 2009). Decreasing the solar elevation requirements would extend the flying season and also the flight hours during a single day. In many climate regions, the typical atmospheric pattern during the day is that the atmosphere is cloudless and clear in the morning, but that clouds appear by noontime and at the time when the solar elevation requirements are met. In Finland this presents a serious limitation. If imagery taken with a low solar elevation were feasible in different tasks, and also from the data quality and automatic interpretation point of views, this would enable more application areas for photogrammetric data.

The new digital photogrammetric cameras have a large dynamic range, which could offer the possibility for decreasing solar elevation requirements from the ones that are conventionally used. Objectives of this study were to investigate theoretically and empirically the influences of solar elevation in modern photogrammetric processes. The motivation behind this study was the need for updating the national guidelines for photogrammetric imaging in the digital era, and similar questions are faced all over the world, too. In order to make our analysis as objective and general as possible, our starting point was to consider the two cutting edge features of novel photogrammetry: automatic point cloud generation by image matching and the spectral reflectance properties of image data. These will, according to our expectations, play a major role in the future, automated photogrammetric applications, and the recent investigations have already indicated the promises and challenges of these processes (Baltsavias et al., 2008; Haala et al., 2010; Markelin et al., 2010b; Heikkinnen et al., in press; Korpela et al., 2011).

First, in Section 2, we will consider, theoretically, the impacts of solar elevation in image radiometry and point cloud generation by image matching. The empirical study is described in Section 3 and the results are given in Section 4. Finally, in Section 5, we draw our conclusions.

2. Influence of solar elevation on the passive imaging process

2.1. Radiometric aspects

Let us first consider the influences of solar elevation on the passive image formation process. In high resolution photogrammetric imaging, the elementary components of radiance entering the sensor are the radiance components from the object of interest, that is to say, the surface-reflected solar radiation, skylight, background radiation and the radiance reflected first by the background objects and then by the atmosphere; the adjacency effect and atmospheric path radiance are radiance components that do not carry any information of the object of interest (Schott, 2007):

\[
L_{\text{at} \text{- sensor}} = L_s + L_{\text{sky}} + L_{\text{bg}} + L_{\text{bg \_ multi}} + L_{\text{adj}} + L_{\text{atm}}. \tag{1}
\]

In the typical topographic mapping scenario with clear atmosphere, the reflected direct solar radiation \(L_s\) is the most interesting reflectance component. The solar irradiance \(E_s\) on a surface is as follows:

\[
E_s = \tau_s E_0^s \cos \theta,
\]

where \(E_0^s\) is the spectral irradiance on top of the atmosphere, \(\tau_s\) is the atmospheric transmittance on the solar path and \(\theta\) is the solar incidence angle on a surface, and where \(\cos \theta\) is given by the vector dot product of the unit vector pointing to the Sun and the unit vector normal to the surface. The surface reflected direct solar radiance entering the sensor is as follows:

\[
L_s(\lambda, \theta, \varphi_1, \varphi_2, \varphi_3) = \rho(\lambda, \theta, \varphi_1, \varphi_2, \varphi_3) \tau_s(\lambda) \tau_v(\lambda) E_0^s \cos \theta / \pi. \tag{2}
\]

where \(\tau_v\) is the atmospheric transmittance in the path from object to sensor, \(\theta\) and \(\theta_v\) are illumination and reflected light (observation) zenith angles, and \(\varphi_1\) and \(\varphi_2\) are azimuth angles, respectively. \(\rho(\lambda, \theta, \varphi_1, \varphi_2, \varphi_3)\) is the bidirectional reflectance distribution function (BRDF), which has to be taken into account with photogrammetric systems having relatively large field of views. BRDF is given as a fraction for the radiation reflected in the direction of the observer divided by the irradiance from the Sun (von Schönermark et al., 2004).

The radiation obtained from the shadowed areas is totally different: \(L_s\) is insignificant and other radiation components dominate. Illumination conditions in shadowed areas are highly variable (Dare, 2005). There are two major types of shadows: the cast shadow and the self shadow. The shadowing object can be opaque or transparent, resulting in full (uniform) shadow or partial (non-uniform) shadow, respectively. Furthermore, with high resolution images it cannot be assumed that the light source is a point source at infinity, in other words, there will not be a definite boundary between shadowed and non-shadowed regions.

The contributions of different radiation components in Eq. (1) are dependent on the atmospheric state, the reflectance properties of the object of interest and the reflectivity of the surrounding objects. The atmospheric effects increase with the view zenith angle and the optical depth, and with decreasing wavelength. More detailed analysis of different factors can be found in von Schönermark et al. (2004) and Schott (2007).

The sensor properties then define how much of and how accurately the incoming radiation is measured. The digital grey value (DN) of a given pixel, after dark pixel substraction is applied, can be given as follows:

\[
\text{DN} = G \omega \int_{0}^{\infty} L_{\text{at} \text{- sensor}}(\lambda) S(\lambda) d\lambda, \tag{2}
\]

where \(G\) is system gain, \(A\) is the area of the detector, \(\Omega\) is the lens solid angle (aperture), \(\tau\) is the integration or exposure time, \(S(\lambda)\) is the system level spectral response, and \(\lambda\) is the wavelength. In the cases of the photogrammetric frame sensors DMC and UltraCam, the amount of radiation entering the sensor is controlled by the aperture and exposure time (Ryan and Pagnutti, 2009), while with line scanner ADS40 only the exposure time is tuned (Beisi et al., 2008). The sensor model in Eq. (4) is given for the Intergraph DMC, which is the sensor used in this investigation (Ryan and Pagnutti, 2009).

The signal-to-noise ratio (SNR) of the sensor has a great influence in image quality. SNR can be expressed as ratio of number of signal electrons \(n_{\text{signal}}\) to noise electrons \(n_{\text{noise}}\) (Sandau, 2010):

\[
\text{SNR} = \frac{n_{\text{signal}}}{n_{\text{noise}}}. \tag{5}
\]

Number of signal electrons can be given as

\[
n_{\text{signal}} = \Phi (h \cdot v) \cdot \tau \cdot A \cdot \eta,
\]

where \(\Phi\) is the intensity, \(h \cdot v\) is the photon energy, \(\tau\) is the exposure time, \(A\) is the area of the detector and \(\eta\) is the quantum efficiency.

Noise sources in CCDs can be divided to sources in time and space (Sandau, 2010). The noise in time can be minimized but not eliminated, while the noise in space can be corrected to a large extent based on calibration information. The noise electrons can be classified into three non-correlated classes: the photon noise (equal to square root of \(n_{\text{signal}}\)), the CCD noise (\(n_{\text{CCD}}\) transfer, dark
current and fixed pattern noise among the others) and the noise of the output amplifier \(n_{\text{AMP}}\). The number of noise electrons is then

\[
n_{\text{noise}} = \sqrt{n_{\text{signal}}^2 + n_{\text{CCD}}^2 + n_{\text{AMP}}^2}.
\]

(7)

It can be shown that with a high light modulation the photon noise dominates, while for the low modulation the CCD and output amplifier noise dominate. With high quality sensor it should be possible to collect images having good quality both in dark areas (especially in shadows) and in bright areas (such as roofs of buildings, sand and snow). The noise becomes typically a problem at signal levels close to the noise floor. Detailed analysis of the noise in CCDs is given by Graham and Koh (2002) and Sandau (2010).

The post-processing is an important part of the radiometric processing line. We consider that for automated photogrammetric applications the desirable output is the directional reflectance factor \(R(x, y, \theta_1, \phi_1, \theta_2, \phi_2)\) or the nadir normalised reflectance factor \(\hat{R}(\varphi)\) (von Schönermark et al., 2004; Schaepman-Strub et al., 2006). The former presumes corrections for the influences of the sensor, atmosphere and shadowing, and cloud removal, and for the latter a further correction of anisotropy of object reflectance has to be carried out. The first implementation of the reflectance calibration of photogrammetric data has been the ADS40 processing line, which has shown promising performance in empirical investigations (Beisal et al., 2008; Markelin et al., 2010b; Korpela et al., 2011).

Previous discussion shows that for the typical image collection process for mapping, the influences of solar illumination should be considered at least in direct sun illumination and in shadows. In the former case, the \(L_s\) is dominating and the central influences of the decreasing solar elevation include the decreasing level of irradiance and the changes in the reflectance of objects due to their anisotropic properties. On the other hand, the areas covered by shadows increase with decreasing solar elevation, and, as the previous discussion shows, the illumination conditions can be highly variable in areas covered by shadows; the \(L_e\) becomes insignificant during such conditions. Finally, the performance is dependent on the quality of the sensor and sensor settings, and post-processing.

2.2. Error budget in photogrammetric point cloud generation

Photogrammetric height extraction is based on stereocopy. The 3D coordinates are determined as the intersection of image rays from multiple images based on the collinear geometrical relationship between the object coordinate and the image point (Kraus, 1993):

\[
x = f(X, X_0, \omega, x_0, a)
\]

(8)

where \(x\) is the image coordinates of object of interest (a vector of dimension \(2 \times 1\)), \(X\) is the coordinates of object point (\(3 \times 1\)), \(X_0\) is the perspective center \((3 \times 1)\), \(\omega\) is the image rotations \((3 \times 1)\), \(x_0\) is the sensor interior orientation \((3 \times 1)\) and \(a\) is additional parameters modelling the image distortions (dimension is dependent on selected model).

The indirect least squares technique provides the 3D coordinates of unknown object points (Kraus, 1993):

\[
y = \begin{bmatrix} A^T W_l A \end{bmatrix}^{-1} A^T W_l b,
\]

(9)

where \(y\) is the vector of unknowns, \(A\) is the design matrix, \(l\) is the vector containing the observations (here the image coordinates) and \(W_l\) is the weight matrix of the observations.

The estimate of the mean square error of individual unknown \(y_k\) is as follows:

\[
\hat{\sigma}_y = \hat{\sigma}_o \sqrt{q_{kk}},
\]

(10)

where \(\hat{\sigma}_o\) is the estimated mean square error of the unit weight. It is obtained from the corrections \(v\) to observations \(l\):

\[
\hat{\sigma}_0 = \sqrt{v^T W_l v / (n - u)},
\]

(11)

where \(n\) is the number of observations and \(u\) is the number of unknowns. The weight coefficients \(q_{kk}\) are the diagonal elements of the inverted normal equation matrix and represent the geometry of the point intersection:

\[
Q = \begin{bmatrix} A^T W_l A \end{bmatrix}^{-1}.
\]

The geometric and reliability aspects of point intersection are discussed by Förstner (1985).

Matching methods can be classified in different ways (Förstner, 1995; Heipke, 1996; Brown et al., 2003). In photogrammetric applications, often signal based matching methods are used, but these methods can be supplemented by, for example, edge-based matching methods. A high performance level is reached with high-quality photogrammetric images, utilizing multiple image overlaps and special matching strategies (Zhang et al., 2006; Baltassavias et al., 2008; Gehrke et al., 2010; Leberl et al., 2010).

In the signal based matching, which is used in this study, the fundamental task is to determine correspondence between overlapping image patches. In the special case with two images, \(g_1(x_1,y_1)\) and \(g_2(x_2,y_2)\), this can be formulated as a task by finding such radiometric model \(f(g_1(x_1,y_2),b)\) and geometric model \((x_2 = f_1(x_1,y_1),y_2 = f_2(x_1,y_1,d))\) that the best fit of two signals is obtained (Ackermann, 1984), that is to say

\[
ge_1(x_1,y_1) + e_1(x_1,y_1) = l(g_1(f_1(x_1,y_1,c),f_2(x_1,y_1,d)),b) + e_2(x_2,y_2).
\]

(13)

\(e_1(x_1,y_1)\) and \(e_2(x_2,y_2)\) is the noise in two image patches and \(b\) and \(c\) are the parameters of the geometric and radiometric models. Each DN in image patches \(g_1\) and \(g_2\) are provided by Eq. (4). The parameters can be solved by the least squares method (Eq. (9)). The precision is dependent on the geometric and radiometric properties of the signals being matched and on the suitability of the geometric and radiometric modelling of the matching method for the task (Förstner, 1995; Brown et al., 2003; Zhang et al., 2006). From the radiometric point of view, the signals (Eq. (4)) must be as similar as possible, and the internal variation in signals has to be large enough, relative to the noise (Eq. (5)), so that the similarity measure exhibits a clear minimum at the correct disparity. The geometric viewpoint is that the variation in disparity within the window must be small enough so that signals of corresponding positions can be properly compared.

The central indicators of elevation extraction performance include the completeness of the extracted height data and the accuracy of the extracted height points. To conclude, the accuracy of the intersected point is dependent on \(\sigma_o\) (Eq. (11)), which is dependent on the accuracy of the matching (Eq. (13)) and the accuracy of the imaging model (Eq. (8)), as well as on the degree of freedom (Eq. (11)) and intersection geometry (Eq. (12)). Only the matching accuracy is directly related to the solar elevation and image radiometry, other factors are related to the geometric issues. In sun-illuminated areas, where the reflected solar radiation dominates, the increase in the anisotropic reflectance properties of objects can reduce the accuracy of matching especially in a situation where the window to be matched contains surfaces with different anisotropic characteristics and they appear different in images being matched (Eq. (3)). In the shadowed areas, the matching quality can deteriorate due to the larger contribution of the image noise and the path radiance (both of which reduce the image SNR) and less stable illumination conditions in non-uniform shadows. In all situations the quality of the sensor will have a great influence.
The completeness of extracted height data is dependent on the same factors as the accuracy.

3. Materials and methods

3.1. Imagery

We collected images over the Hyytiälä Forestry Research Station in Finland (62°N, 24°E) (Korpela et al., 2011). The area is a typical Finnish forest scene, with the addition of some lakes, roads and fields (Fig. 1). We carried out the campaign during the full-leaf season on 31 May 2009 using the photogrammetric imaging system of the National Land Survey, which consisted of an Intergraph DMC digital photogrammetric large-format camera, an Applanix POS AV 510 GNSS/IMU and the stabilized camera mount of the Intergraph. The system has been described in more detail by Honkavaara et al. in a recent study.

Images were collected using nominal flying heights of 2, 3 and 4 km above the ground level. We analyzed single strips from the morning and noon data from each flying height. The ground sampling distances (GSDs) were 20, 30 and 40 cm for high resolution panchromatic images and 1.0, 1.2 and 1.6 m for low resolution multispectral images, which composed of blue (B), green (G), red (R) and near-infra-red (NIR) channels. The solar elevations were 25–28° in the morning and 44–48° at noon time. The forward overlaps were 80% at a flying height of 2 and 3 km and 60% at a flying height of 4 km. The imaging conditions were excellent, with an average visibility of 45 km and an aerosol optical thickness (AOT) at 500 nm of about 0.058 during the morning and 0.075 during the noontime flight. When selecting the exposure settings, the objective was to obtain a similar dynamic range for each block; the settings were kept constant within a single block. Details of the atmospheric conditions and the exposure settings are given in Table 1.

We geometrically and radiometrically processed the images using standard Intergraph DMC post-processing software. We processed the high-resolution, large-format panchromatic images and low-resolution, multispectral images to sensor native 12 bit pixel depth without using any colour adjustments.

3.2. Radiometric processing

The radiometric ground truth included five portable reference reflectance targets 5 × 5 m in size, and with 0.05, 0.20, 0.25, 0.30 and 0.50 nominal reflectance. The nadir reflectance spectrums of the reference targets were measured using an ASD Field Spec Pro FR spectroradiometer during the morning and noon flights, and the measurements were normalized to a calibrated white 30 cm by 30 cm Spectralon reference standard from Labsphere. We weighted the target reflectances with the DMC channel spectral sensitivities to obtain the reflectances per multispectral channel. We obtained the reference reflectance in exact viewing and illumination geometry for each image by scaling the field reference measurement using the anisotropy factors based on the laboratory goniospectrometer measurements by FIGIFIGO (Suomalainen et al., 2009). The average accuracy of the reference was estimated to be better than 5%.

We carried out the vicarious radiometric sensor calibration using the methodology developed by Markelin et al. (2010a,b). We calculated the reference target DN values as averages in small image windows. With the panchromatic images, the windows were 12 × 12, 8 × 8 and 4 × 4 pixels for flying heights of 2, 3 and 4 km, respectively; with the multispectral images, the window sizes were 4 × 4, 2 × 2 and 1 × 1 pixels, respectively. We scaled the DNs using the camera aperture size and exposure time. We calculated the at-sensor radiances for each reference reflectance target and DMC channel using MODO software (a graphical front end to MODTRAN4 radiative transfer code), based on in situ reflectance and atmospheric measurements, and determined the linear radiometric sensor model. We obtained atmospheric data for the radiative transfer calculations from the SMEAR-II weather station (horizontal visibility, ground temperature and CO2 concentrations) (SMEAR, 2009) and the NASA AERONET station (H2O and O3 concentrations) (Holben et al., 1998), which are located at Hyytiälä.

We used the empirical line-based method, modified to take into account the anisotropy of the object reflectance, to carry out the reflectance calibration (Honkavaara et al., 2011). We calculated the calibration for each channel by using five reference tarps (similar window sizes were used as in the vicarious radiometric sensor calibration). This procedure will provide band averaged bi-directional reflectance factors (BRFs) with an estimated accuracy of better than 5% in areas that are in similar illumination conditions as the reflectance targets; in other areas (especially in shadowed areas) the values are not reflectance factors.

3.3. Geometric processing

We performed aerial triangulation using the Bae Systems SOCET SET Multisensoral Triangulation Software (Version 5.5.0) (Walker, 2007). In the self-calibrating, GNSS/IMU supported bundle block adjustments, we solved the boresight parameters, principal point and principal distance, radial distortions and asymmetric decentering distortions. We used 9–10 targeted points as ground control...
points (GCPs) and the remaining 17–18 targeted points as independent checkpoints; standard deviation of points was 5 cm. Calculations were carried out in the ETRS-TM35FIN coordinate system. The optimal parameterisation for the DMC images would be to use sensor specific, multi-head additional parameters, but we decided to use standard single-head parameters that were supported by the software. Some level of accuracy reduction and systematic block deformations are expected (Alamús and Kornus, 2008; Honkavaara et al., 2011), but this was not considered as a problem in this study, where most of the evaluations were carried out in local areas in a way that the random error component will represent the systematic error-free situation.

We used SOCET SET Next Generation Automatic Terrain Extraction software (NGATE) to generate point clouds from panchromatic images (Zhang et al., 2006; DeVenecia et al., 2007). The matching strategy engaged edge- and correlation-matching methods and applied image pyramids and back matching, but the correlation matching was the primary matching method. We optimized the matching parameters for the forest environment by using small correlation window sizes (an image correlation window size was 11 × 11 pixels) and by allowing for large height differences and large search spaces. We generated a triangulated irregular network (TIN) model and the anticipated point density was approximately the GSD of the images (20, 30 and 40 cm, respectively).

### 3.4. Performance assessment

We calculated various statistics to characterize the point cloud quality. We evaluated the absolute height error by using targeted GCPs, while we obtained the relative height error by comparing different point clouds. We used height variation in planar windows to characterize the internal precision of matching. We determined the height differences of two point clouds so that for each point in the point cloud under evaluation, we interpolated a reference height from the reference point cloud. We used the average from the height differences to characterize the systematic height error and the standard deviation from the height differences to indicate random error; the root-mean-square-error (RMSE) is the combination of systematic and random error components. In all calculations, we considered differences that were larger than 3 times the standard deviation as outliers and eliminated them iteratively from the calculations.

We used the relative point density as an indicator of the success rate:

\[
R = \frac{\text{point}\_\text{density}_{\text{pc}}}{\text{point}\_\text{density}_{\text{theor}}} = \frac{\text{point}\_\text{density}_{\text{pc}}}{(1/\text{GSD})^2}.
\]

(14)

where point density\_pc is the point density per square meter in the point cloud and point density\_theor is the theoretical point density based on the selected point interval (in this investigation the GSD).

We selected one stereo model from each block containing the radiometric test field for detailed analysis (Fig. 2): for the 4 km imagery, we used a stereo model with a 60% forward overlap, whereas we carried out most of the analysis for the 2 and 3 km image blocks using a stereo model with an 80% overlap; however, we also conducted some analysis using a stereo model with a 60% overlap. The stereo models from the morning and noon flights covered the same area. We performed different analyses in the following manner:

1. The overall performance of image matching was evaluated by dividing the stereo model into a 5 by 3 grid, and the relative point density (Eq. (14)) was calculated for each square (3 squares in flight direction).
2. The target-specific quality of DSMs was evaluated by selecting 80 m by 80 m squares from the open areas (fields or logging areas) and from the forests. In each stereo model, the objective was to use five areas representing both object types, distributed as uniformly as possible, but this objective failed, in some cases, with the open areas (Fig. 2). The performance was evaluated as the function of the relative radial distance from the center of the stereo model:

\[
\text{Relative radial distance} = \frac{\text{Radial distance}}{\text{Maximum radial distance in stereo model}}.
\]

(15)

Negative sign was given to relative distances that were in the western side of the stereo model base, and positive sign for the eastern side. Relative distance was used to be able to compare results of stereo models collected from different flying heights.
3. Height extraction performance in directly sun-illuminated and shadowed fields and roads were evaluated (Fig. 2). In fields, 10 windows at a size of $3 \times 3$ m were analyzed from shadowed and directly sun-illuminated areas (seven of the areas were covered by vegetation and three were without vegetation). In the morning, 10 windows were in full shadow and 10 windows were directly illuminated by the sun. At noontime, all of windows were directly illuminated by the sun. For the road areas, approximately 100 shadowed and sun-illuminated windows, $3 \times 3$ m in size, were used. In the morning, all of the shadowed windows were in shadow, while at noon the windows were, in many cases, illuminated by the sun. Twenty shadowed and 20 sun-illuminated asphalt road windows and 20 gravel road windows were selected for further radiometric and geometric evaluations.

4. Twenty coniferous and 20 deciduous trees were used for the analysis of reflectance.

The observation zenith angles of different objects were not extreme (less than 23$^\circ$), and the differences in the angles between the images in the stereo models were relatively small (in relative azimuth angles $(\phi_r-\phi_i)$, less than 40$^\circ$ and, in zenith angles, only a few degrees), thus large anisotropy differences are not expected to appear in stereo models.

To evaluate general radiometric quality of the images, we calculated grey value histograms and several histogram statistics. We carried more detailed evaluations of targets 2–4: we considered reflectance spectrums and characterized image dynamics by calculating variation coefficients in small image windows:

\[
\text{variation coefficient} = \frac{\text{standard deviation of DNs}}{\text{average DN}}.
\]

4. Results

4.1. Radiometric properties of collected images

Histograms of strips collected in the morning and in the noon are shown in Fig. 3. Histograms of blue, green and red channels had one peak, while the NIR histogram had two peaks, one for the water and one for the other areas. The NIR histogram was the most widely spread, while the histograms of other channels were narrower and had a similar width. On individual channels, the 99% efficiency of image histograms (that is to say, the width
morning data, n: sun-illuminated noon data, n

gravel and field targets in shadow and in direct solar illumination

similar in each flying height. Moreover, the histograms from the
grams, which is because of the fact that the image content is quite

morning) to 2015 (NIR channel, GSD 20 cm, morning). To conclude,
cator of dynamic range) varied from 348 (blue channel, GSD 20 cm,

Variation coefficient in panchromatic images in different objects calculated in small

and in sun illumination in noon; P50: reflectance tarp with nominal reflectance 0.5.

We evaluated the DN variations of the tarpaulins and asphalt,
gravel and field targets in shadow and in direct solar illumination
in panchromatic images (Table 2). The coarser the material, the
higher the variation coefficient was. The variation coefficients
were the lowest (0.01–0.02) for the tarpaulins and the highest
(0.07–0.14) for the sunny field. With asphalt, gravel and field targets
in sun illumination, the coefficient of variation was 30–50%
higher in the morning than at noontime; in tarpaulins the differ-
ences were less than 10%. Most likely, the higher variation coef-
ficient value in the morning was due to larger contrasts in the
image windows with lower solar elevation. In fields, the variation coefficient was 2.5–3 times higher in sun illumination than in
shadows, which indicated lower image dynamics in shadows.
On roads, the differences of variation coefficients in shadows
and sun illumination were much lower; most likely, the possible
reduction of the signal variation in the shadows was compen-
sated for by the non-uniformity of illumination and other noise
sources.

We studied theoretically the relationship between the object
reflectance and at-sensor radiances and DN’s by using the radiance
and reflectance calibration values (Section 3.2). Results showed
that reflectance that will cause saturation of DN’s was 0.7–0.9 on
blue and green channels, about 1.0 on the red channel, 1.1–1.3
on the NIR channel and 1.0–1.1 on the PAN channel; values were
quite similar for the morning and noon. Values greater than one
indicate that with the settings, the maximum reflectance of 1.0
could be recorded without saturation.

These results indicated that the camera exposure settings were
selected successfully for producing similar target DN’s at different
times, even though, in reality, the level of solar irradiance in
the morning was roughly 60% of the irradiance level at noontime.

4.2. Analysis of reflectance data

We studied the reflectance spectrums and reflectance variations
of different objects. As discussed in Section 3.2, the reflectance
calibration is accurate only for objects directly illuminated by the
sun.

Reflectance spectrums in shadowed and sun-illuminated fields
with vegetation are shown in Fig. 4a (average spectrums of seven
windows of size 3 × 3 m). For the sunny fields, the spectral signature
was typical of that for vegetated surfaces and the minimums and
maximums (not shown in figure) varied from between 0.02 and
0.07 for the blue channel to between 0.20 and 0.30 for the NIR
channel. The morning and noon reflectance values were significantly dif-
fent in the red channel, which can be due to a different view/
illumination geometry; in the morning, the field points were in the
backward scattering (non-shadow) direction, while at noontime
they were in the forward scattering (shadow) direction. For the
shadowed fields, the reflectance variation was dramatically re-
duced, showing minimum and maximum reflectance values of
0.00–0.02 in all of the channels, and the spectral signatures were
uniform and completely different from the signatures in the sun
illumination.

Shadowed and sun-illuminated reflectance data for the asphalt
surfaces showed quite similar behaviour as with the field data
(Fig. 4b) (average spectrums of 20 windows of size 2 × 2 m).
In shadows, the average road reflectance varied in different channels
from between 0 and 0.02 for the NIR channel to between 0.01 and
0.03 for the blue channel. On sun-illuminated roads, the reflect-
ce values varied from between 0.14 and 0.16 for the blue chan-
tle to between 0.17 and 0.21 for the NIR channel. The standard
deviation in reflectance spectrums measured at different flying
heights was clearly larger for the morning data (4–7%) than for
the noontime data (0–4%), which is most likely due to the BRDF ef-
fects, which were larger in the morning.

We calculated the average reflectance spectrums of 20 conifer-
ous and 20 deciduous trees (average reflectance values of 20 trees,
window size 2 × 2 pixels in 2 km data and 1 pixel in 3 and 4 km data).
The averaged reflectance spectrums of coniferous trees is shown in Fig. 4c; deciduous trees (not shown here) showed much
higher values in the NIR channel, as expected, but the general
behaviour was similar. A rather large variation appeared in the
reflectance measurement from different flying heights, which is
due to the fact that the view-illumination geometry in different
flying heights was different, which caused differences in BRDF ef-
facts. The plot of minimum, maximum and average reflectance values for the 80 × 80 m forest sample windows in the panchro-
matic channel in Fig. 4d demonstrate the BRDF effects. In the
morning, the block was flown close to a south–north direction
and the sun illumination came from the east, which caused the
western side (non-shadow, backward scattering) of the stereo
model to be bright, and the eastern side (shadowed, forward scat-
tering) to be dark; the solar principal plane (where the BRDF ef-
facts are the largest) was in the direction perpendicular (about
west–east) to stereo model base. The noon flight was flown close
to the direction of solar illumination; thus, the backward scat-
tering side was in the flying direction in northern side of the model
and the shadowed side was in the southern side of the model;
the principal plane was in the base direction (about south–north).
The BRDF effects were smaller at noontime, as the angular range in
the principal plane was smaller (about ±15°) than in the morning
(about ±30°). Further variation is caused by the forest type, which
was not considered in this study. Because of the BRDF effects, the
reflectance variation in forests was higher for the morning data
than it was for the noontime data. The minimum reflectance
was on the level of 0 in the morning and at noontime (the slightly
negative value is due to a small inaccuracy in the reflectance cal-
boration) and the maximum reflectance values were 0.13–0.29 for
the morning and 0.09–0.20 at noontime at different flying heights,
and varied depending on the type of forest and illumination/shad-
owing condition.

<table>
<thead>
<tr>
<th>Flying height (km)</th>
<th>Shadow coefficient</th>
<th>Sunny coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>N = 7</td>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td>3 × 3 m</td>
<td>4</td>
<td>0.03</td>
</tr>
<tr>
<td>Asphalt</td>
<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>N = 20</td>
<td>3</td>
<td>0.04</td>
</tr>
<tr>
<td>2 × 2 m</td>
<td>4</td>
<td>0.03</td>
</tr>
<tr>
<td>Gravel</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>N = 20</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>2 × 2 m</td>
<td>4</td>
<td>–</td>
</tr>
<tr>
<td>PS2</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>N = 1</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>2 × 2 m</td>
<td>4</td>
<td>–</td>
</tr>
</tbody>
</table>

For each object number and size of windows are given; N: number of windows, m: morning data, n: sun-illuminated noon data, m: windows are in shadow in morning and in sun illumination in noon; PS2: reflectance tarp with nominal reflectance 0.5.
The analysis of roads in forest shadows was complicated. Because of the surrounding trees, the road point windows of size 3 × 3 m could also include other objects (mainly trees, tree branches). In some situations it appeared that the quality of measurement of road surface was better in sun illumination; this is demonstrated in Fig. 6. In quantitative evaluation, significantly larger portion of 3 × 3 m windows were planar in sun-illuminated conditions than in shadowed conditions (windows with height differences lower than 1 m were considered as planar). We carried

4.3. Success rate of point cloud extraction

Relative point densities in different areas (5 by 3 grid) of the stereo models were calculated. We obtained relative densities as low as 0.50 in squares with large water areas, but in textured areas the relative densities were higher. The morning and noontime densities in open areas, slightly better with the morning data. The differences between point densities in morning and afternoon were in open areas, 0–23% (Fig. 5a), and in forest areas, 2–27% (Fig. 5b). Closer visual evaluation of point clouds showed that the matching succeeded as expected in every pixel. Failures were mostly observed in closure to thin 3D objects, such as thin trees or poles. The unanticipated results were with the 4 km image data in the open area at the eastern side of the stereo model; large areas with matching failures appeared both in the morning and noontime flight data (success ratio of 0.2–0.4 in Fig. 5a); trials with different stereo models did not provide successful matches in this area. The object was a ploughed, tilted field with repetitive linear features, but in some other cases similar objects were successful. This is probably a shortcoming of the software.

The point density was slightly lower in shadowed fields than in sun-illuminated fields (Table 3). For the points that were in shadow in morning and illuminated by the sun at noontime, the difference in point density was 1–17%. For the fields that were illuminated by the sun both in the morning and at noontime, the point densities were about 10% higher in the morning for 2 and 3 km data, and more similar in the morning and at noontime for 4 km data. The relative point densities were 0.73–0.91 in the shadowed fields and 0.81–0.98 in the sun-illuminated fields.

Fig. 4. Reflection properties of different targets in different flying heights. (a) Spectrums from left: shadowed field (morning), sunny field (morning) and sunny field (noon). (b) As in a for asphalt. (c) Spectrums of coniferous trees in morning (left) and noon (right). (d) Minimum (min), maximum (max) and average (av) reflectance in 80 × 80 m forest windows in panchromatic data collected with 4 km flying height in morning (m) and noontime (n) (as the function of the relative distance from the stereo model center, Eq. (15)).
The accuracy of aerial triangulation was, at independent checkpoints, 0.2–0.4 times the GSD on the horizontal coordinates and 0.5–0.75 times the GSD (0.05–0.075% of flying height) on the height coordinate (Table 4); these are typical accuracy results for this type of block. Morning data provided slightly better results, but the differences were small.

We carried out the following accuracy evaluations using point clouds derived from single stereo models. The expected error in the height measurement from a single stereo model is provided by the error propagation. Theoretical errors for the stereoscopic measurement with a matching error of \( e_{\text{matching}} = \text{GSD}/4 \) are given in Table 5. When the stereo overlap increases from 60% to 80%, the expected error values are doubled. According to error propagation with a constant parallax measurement error, the expected height error is similar throughout the entire area of the stereo model, but the horizontal point determination error is at a minimum at the centre of the stereo model and increases with the distance from the model’s centre (Kraus, 1993). We calculated the absolute error of DSMs with 60% and 80% stereo overlaps using the signalized control points as a reference (Table 5). Between 7 and 13 checkpoints were available in the stereo models. With 60% overlaps, the random height error was 0.18–0.35 m, 0.17–0.24 m and 0.27–0.29 m for flying heights of 2, 3 and 4 km, respectively. Increasing the stereo overlap from 60% to 80% caused a 1.3– to 2.3-fold increase in the random height error, which is relatively close to the expected 2-fold deterioration. The random errors were on the level of theoretical estimates based on a matching error of GSD/4 in all cases excluding the 2 km noon data (in this data, one point with high error caused the higher than expected random error). Quite large systematic errors appeared with the 3 and 4 km data, which can be due to the fact that the processing was not optimized for absolute accuracy because the software did not support the use of the accurate DMC sensor model; we compensated for all systematic model deformations in the following local height error evaluations. Despite the possible systematic errors, the RMSE was mostly on the level of GSD or better on stereo models with 60% overlap.

We calculated the differences for the morning and noontime forest and open area grid DSMs of size 80 × 80 m and with 1 × 1 m grid spacing. Examples of DSMs and the difference surfaces are shown in Fig. 7, and statistics for the differences are shown as the function of the relative radial distance from the model centre in Fig. 8. In open areas, the systematic difference was

### Table 3

Average values of relative point density in 3 × 3 m planar field, asphalt and gravel windows in shadows and in sun illumination.

<table>
<thead>
<tr>
<th>Object</th>
<th>Flying height (km)</th>
<th>Relative point density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Shadow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Field</td>
<td>2</td>
<td>0.86</td>
</tr>
<tr>
<td>N = 10</td>
<td>3</td>
<td>0.91</td>
</tr>
<tr>
<td>4</td>
<td>0.73</td>
<td>0.89</td>
</tr>
<tr>
<td>Asphalt</td>
<td>2</td>
<td>0.84</td>
</tr>
<tr>
<td>N = 20</td>
<td>3</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>0.89</td>
<td>1.00</td>
</tr>
<tr>
<td>Gravel</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>N = 20</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>0.99</td>
</tr>
</tbody>
</table>

N: number of windows, m: morning, n: noon, n*: windows are in shadow in morning and in sun illumination in noon.

### 4.4. Accuracy of the height data

The accuracy of aerial triangulation was, at independent checkpoints, 0.2–0.4 times the GSD on the horizontal coordinates and 0.5–0.75 times the GSD (0.05–0.075% of flying height) on the height coordinate (Table 4); these are typical accuracy results for
–0.10 to 0.20 m and it varied quite randomly with the radial distance; random differences were 0.10–0.20 m, and, on average, were lowest for the 2 km data and highest for the 3 km data (Fig. 8a). In forest areas, the systematic difference was −0.30 to −0.75 m for the 2 and 4 km data, and −0.5 to −1.5 m for the 3 km data; the random differences were 1–3 m (Fig. 8b). The large differences in forest DSMs can be explained by the vagueness of the measured points, uncertainties in matching caused by large disparities in the forest windows, and large height variations in the forests in general; small planimetric difference in the models will cause large height differences. The systematic differences in forests indicated that the height measurements with the low solar elevation data were systematically above the height measurements with higher solar elevation data, while the low systematic differences in open areas indicated that this difference was not caused by systematic block deformations. A possible explanation for this performance is that the software might have managed to measure lower points inbetween the trees when the solar elevation was higher. According to these results, the height error was not dependent on the radial distance.

We carried out evaluations of point clouds in the field and road areas for shadowed windows and windows directly illuminated by the sun that were each 3\(\times\)3 m in size. The visual examination indicated that there were height artefacts in areas shadowed by trees (Fig. 9, see also Fig. 6). Quantitative evaluation showed that the planar field windows had random height variations of 0.22–0.32 m in the shadows and 0.06–0.15 m with direct sun illumination (average values in 10 windows); the variations were 2–3 times higher in shadowed windows than in sun-illuminated windows (Table 6). For planar road windows, the random height variations were 0.23–0.30 m and 0.09–0.20 m, in shadows and direct sun illumination, respectively (Table 6). The differences of point clouds derived using morning and noontime images with a similar GSD showed 65–80% larger height differences in shadowed areas. All the previous results showed that performance was lower in shadowed areas.

### Table 4
RMS errors at targeted checkpoints after aerial triangulation at different flying heights.

<table>
<thead>
<tr>
<th>Flying height (km)</th>
<th>Morning RMSE (m)</th>
<th>Noon RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>0.12</td>
</tr>
</tbody>
</table>

### Table 5
Statistics of DSM height errors at targeted checkpoints on stereo models with different overlaps. Theoretical value is given for the matching error of GSD/4.

<table>
<thead>
<tr>
<th>Flying height (km)</th>
<th>Overlap (%)</th>
<th>Theoretical (m)</th>
<th>Morning (m)</th>
<th>Noon (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Syst</td>
<td>Rand</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>0.33</td>
<td>−0.12</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>0.16</td>
<td>−0.04</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>0.49</td>
<td>−0.21</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>0.24</td>
<td>−0.31</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>0.33</td>
<td>−0.31</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Syst: systematic error; Rand: random error.
Fig. 7. Examples of DSMs extracted on (a) open area and (b) forest objects from images collected from 2 km flying height. From left: morning DSM, noontime DSM and their difference.

Fig. 8. Random and systematic differences in (a) open area and (b) forest DSMs of size \(80 \times 80\) m derived from morning and noon stereo models (noon – morning), as the function of the relative distance from the stereo model center (Eq. (15)).

Fig. 9. An example of artefact in a point cloud in shadowed area. Left: Panchromatic airborne image collected in morning from 2 km flying height. Center: Point cloud derived from the morning image data with shadows. Right: Point cloud derived from the noon image data without shadows.
### 5. Discussion and conclusions

We have considered theoretically and empirically the influences of solar elevation in image radiometry and in automatic point cloud generation by image matching. We collected the image data in this study using the high performance photogrammetric system Intergraph DMC of the National Land Survey of Finland. The photogrammetric processing environment at the FGI consisted of the Bae Systems Socet Set with NGATE terrain extraction software. Detailed characterizations of the imaging system and processing environment by Markelin et al. (2010a) and Honkavaara et al. (2011) were the basis for the test design.

#### 5.1. General performance of automatic point cloud generation

Our objective was to provide point clouds with a point density corresponding to the GSD. Typically, the matching was successful in every pixel. It is unavoidable that matching fails in occluded areas and on water surfaces. Thin objects were also difficult to measure using the method. Some unexpected failures also occurred, which were most likely shortcomings of the software and hopefully will be improved in future versions of the software.

We carried out terrain extraction mostly in individual stereo models in order to keep the traceability to the matched images. In practical applications, multi-image matching is performed, which will increase the point densities and improve the point cloud accuracy towards the accuracy of aerial triangulation, that is to say, in well-defined objects to a level of 0.5 times the GSD for the horizontal coordinates and better than the GSD for the height. Single-stereo-model-based measurements are, however, also possible with multiple image solutions; the image overlaps and obstructions together determine the number of images available for matching at a certain object point.

The absolute height accuracy of well-defined objects derived from single stereo models were on the level of 0.5–2 times the GSD, which is close to the values that are obtained with a matching error of GSD/4, and consistent with other recently presented accuracy results (Haala et al., 2010). Improving the base-to-height ratio improved the accuracy, as expected. The results did not show a deterioration in height accuracy as the function of radial distance from the centre of the stereo model, which could have been possible due to the decreasing resolution towards image border (Honkavaara et al., 2011). The random and systematic differences between morning and noontime point clouds were both about 20 cm at all flying heights on relatively flat open terrain, which indicates very good repeatability; the differences in the forests were larger, which was as expected and consistent with recent results (Baltsavias et al., 2008; St-Onge et al., 2008). The processing was not optimized to provide the highest absolute accuracy, as we did not model the special multi-head distortions of the DMC images due to the limitations of the photogrammetric software. Recent developments with photogrammetric cameras indicate that the geometric modelling of large-format sensors will be better controlled in the future (Jacobsen et al., 2010), and photogrammetric sensors will be increasingly realized as single-head constructions. All results indicated very high performance of photogrammetric point cloud generation.

#### 5.2. Influences of solar elevation

The radiometric evaluation of the DN statistics for the image strips collected from 2, 3 and 4 km flying heights and with low (25–28°) and normal (44–48°) solar elevations showed that the sensor settings could be tuned successfully to provide similar histograms from different flying heights. In sun-illuminated areas, we could not detect any deterioration of performance with decreasing solar elevation, which was expected based on theoretical considerations. Problems were detected with shadows, which approximately doubled the areal extent in the lower solar elevation data. The spectral signatures and image dynamics were reduced in the shadows. It was shown that the random errors in height measurements were higher in areas shadowed by trees than in areas in direct solar illumination. Furthermore, success ratios were slightly lower in areas shadowed by trees than in sun-illuminated areas and, in particular, the probability of measuring the correct terrain surface with deep shadows decreased. We also observed that the forest DSM derived using images with a lower solar elevation was, on average, above the DSM derived using image data with a higher solar elevation; also, this behaviour could be due to problems with matching in shadowed areas.

The results of the empirical study are related to specific technical solutions and external conditions. The DMC sensor is a high-quality photogrammetric sensor; noisier and less stable sensors will not provide similar results. We collected the images under very clear atmospheric conditions. Because of this, the amount of diffuse light was low, which can highlight the problems in the shadowed areas. On the other hand, a hazier, less stable atmosphere might cause other problems, for example, it can cause critical increase in noise level in shadowed areas. We obtained the results during full-leaf season, which provides the highest performance in point cloud generation in forest areas (Baltsavias et al., 2008). The exposure settings were successful but less successful settings will reduce the data quality.

We detected the problems with shadows with NGATE software, which used correlation-based matching; it can be assumed that this is a typical performance when using this approach. Other matching approaches might have different behaviour. The time differences between images in the stereo models were only a few seconds; bigger errors will be expected if the time differences between images are larger. Problems are expected especially if the images from different strips are matched together. Evaluations were carried out in tree shadows; illumination conditions in the tree shadows are not uniform (Section 2.1), which might be reason for the reduced height measurement precision; in uniform shadow situation can be different.

The study site was a forest site, and it will be important to also extend the evaluations to other types of scenes, like urban areas. Specific objects that we evaluated in this study were field and road surfaces and a forest canopy surface. Even this relatively limited investigation showed that different objects had different behaviour.

#### 5.3. Future prospects and recommendations

This project was related to the national need for updated recommendations for solar elevations in photogrammetric data

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**Table 6**

AVERAGE HEIGHT VARIATION IN 3 X 3 M PLANAR FIELD AND ROAD WINDOWS IN SHADOWS AND IN SUN ILLUMINATION.

<table>
<thead>
<tr>
<th>Object</th>
<th>Flying Height (km)</th>
<th>Height Variation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Shadow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Field</td>
<td>2</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.22</td>
</tr>
<tr>
<td>Asphalt</td>
<td>2</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.23</td>
</tr>
<tr>
<td>Gravel</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>–</td>
</tr>
</tbody>
</table>

N: number of windows, m: morning, n: noon, n*: windows are in shadow in morning and in sun illumination in noon.
collection flights for topographic mapping. With the evaluated data, the object was measurable with the solar elevation of 25°. But as our theoretical considerations showed, the solar elevation, atmospheric conditions, and the sensor and its settings together have a great influence on the quality of the collected image data. This means that optimization of the solar elevation must be related to the performance of the imaging system, which should be based on the reliable characterization of the system in a laboratory or at a test field (Honkavaara et al., 2011). A further advantage of the characterized systems is that the limiting atmospheric and illumination conditions could be determined based on simulations (Börner et al., 2001). Also the processing methods and the object being studied should be considered. The basic processes in the photogrammetric processing line include data collection, geometric and radiometric data referencing (or correction) and various measurement and interpretation applications (Honkavaara et al., 2009), which are briefly discussed in the following.

Automatic aerial triangulation represents a fundamental step in the photogrammetric georeferencing process, and it is based on image matching. The diverse effects of shadows on automatic tie point measurements were detected in previous studies (Wang and Madani, 2004). If the automatic tie point measurement is sensitive to shadows, the risk of deterioration in the accuracy of the results increases with increasing areas covered by shadows. High radiometric performance is one of the key aspects in new generation digital photogrammetric processes, and reflectance-calibrated image data is one possible future output product. Although the new approaches for the reflectance calibration of photogrammetric data have provided promising results (Beisl et al., 2008; Markelin et al., 2010b), shadows have been identified as challenging from the point of view of quantitative remote sensing (Heikkilä et al., in press; Korpela et al., 2011). This is due to the difficulty in obtaining adequate reflectance calibration in shadows, and the current approaches do not even carry out the reflectance calibration accurately in shadows. Also our results showed that the radiometric quality of image data was reduced in shadows.

Problems with shadows in digital photogrammetric cameras have been reported in interactive stereo mapping applications (Spreckels et al., 2010). Important questions pertain to the capability of the stereo mapping/interpretation software to adapt to sun-illuminated and shadowed areas in a single view (this is also an issue of productivity) and how the image details are reduced in shadows. Challenges with shadows could be compensated for by using more advanced methods for mapping the high dynamic range images to lower dynamic range monitors (Reinhard et al., 2010) and with automatic shadow correction methods (Dare, 2005).

Automatic point cloud generation is one of the new innovations in photogrammetric processing and expected to play an increasing role in the future photogrammetric applications (Zebedin et al., 2006; DeVenecia et al., 2007; Baltsavias et al., 2008; St-Onge et al., 2008; Haala et al., 2010; Gehrke et al., 2010; Leberl et al., 2010). Recent results indicated that shadows caused problems for point clouds (Haala et al., 2010). This study provided a framework for evaluating influences of image radiometry (and solar illumination) in photogrammetric processes and gave new quantitative proof of the influences of shadows. The analysis showed that consideration of radiometric aspects is crucial in the context of point cloud generation, because the image radiometry has a direct influence on the quality of a point cloud. Further studies should be carried out to find relationship of the point cloud quality and applications.

Automated interpretation processes, such as automated map updating, will gain on using quantitative, multispectral information in digital photogrammetric data. One typical way of utilizing spectral information is to use supervised methods and calibrate the classifier using training data set (Zebedin et al., 2006). Another approach would be to utilize physical reflectance information of objects derived from the images (von Schönermark et al., 2004). The data for sun-illuminated and shadowed areas can be approached by carrying out shadow corrections (Dare, 2005) or by separating the analysis of the shadowed and sun-illuminated areas (Le Bris and Boldo, 2008; Korpela et al., 2011). The very high resolution methods utilizing photogrammetric images are still under development, and it is unknown how well these different approaches adopt to changing radiometric properties caused by shadows and changes in view-illumination geometry, which were also demonstrated in this investigation.

From the points of view of usability of photogrammetric systems and the general needs, it is important to be able to utilize data collected with lower solar elevations, for example as low as 10° from the horizon. Information about the environment is also needed in conditions deviating from those used conventionally in mapping, for example after catastrophes such as storm damage. Also in these situations, it is important that the interpretations are as highly automated as possible. It is thus important to develop methods that are not so sensitive to changes in solar illumination geometry and shadows.

We would like to emphasize that the performance assessments of different methods should give quantitative information about the radiometric properties of image data, including atmospheric conditions, solar elevation, the quality of the imaging system, sensor settings and the resulting image quality parameters, and the data processing level, and include an analysis of the performance in shadows too.

5.4. Concluding remarks

The motivation behind this investigation was to provide new national recommendations for solar elevation in photogrammetric mapping, which is a relevant issue all over the world. We presented a framework for the considerations of impacts of solar illumination in photogrammetric applications. Our starting point was to consider the automatic point cloud generation and reflectance signatures of objects, as we expect that in the very near future these will be the basic derivatives of photogrammetric image data, and the basis of automated, new-generation photogrammetric applications. The considerations and results indicated that the major problems are expected in shadowed areas, which increase their areal extent when the solar illumination decreases. In this study, the quality of automatically derived point clouds was lower in shadowed areas than in sun-illuminated areas, and also the quality of reflectance calibration and radiometric quality of images were reduced in shadows. It was emphasized that it is important to develop such algorithms that are not sensitive to shadows. This is due to fact that automatic interpretation of data will be necessary in the future in the shadowed conditions, especially, in order to improve the productivity and cost-efficiency of the photogrammetric mapping and to enable the efficient use of photogrammetric technology in wide variety of application areas, such as in disaster mapping. Furthermore, shadows cause problems also in visual applications, such as stereo mapping or visual evaluation of images over the Internet. Important factors influencing the usability of the image data collected with low solar elevation are also the quality of the imaging system, especially the signal-to-noise ratio, as well as the quality of the exposure settings during the data collection. In further evaluations it is important to consider the influences of atmospheric state; our data was collected under very clear atmospheric conditions. Finally, we would like to emphasize that the empirical data collected with solar elevation range of 25°–48° that was used in this investigation provided excellent results when concerning the automatic point cloud generation and image radiometry.
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