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

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ABSTRACT

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 increased 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.

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

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photogrammetric production lines of European Mapping Agencies revealed the overall insufficiency of radiometric data processing (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; Heikkinen 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 (L_{at_sensor}) are the radiance components from the object of interest, that is to say, the surface-reflected solar radiance (L_s), skylight (L_{sky}), background radiance (L_{bg}) and the radiance reflected first by the background objects and then by the atmosphere (L_{bg_multi}); the adjacency effect (L_{adj}) and atmospheric path radiance (L_{atm}) are radiance components that do not carry any information of the object of interest (Schott, 2007):

$$L_{at\_sensor} = L_s + L_{sky} + L_{bg} + L_{bg\_multi} + L_{adj} + L_{atm}. \tag{1}$$

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_λ) on a surface is as follows:

$$E_\lambda = \tau_s E_\lambda^0 \cos\theta, \tag{2}$$

where E_λ^0 is the spectral irradiance on top of the atmosphere, τ_s is the atmospheric transmittance on the solar path and θ 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:

$$L_s(\lambda, \theta_i, \varphi_i, \theta_r, \varphi_r) = \rho(\lambda, \theta_i, \varphi_i, \theta_r, \varphi_r)\tau_s(\lambda)\tau_v(\lambda)E_\lambda^0 \cos\theta/\pi, \tag{3}$$

where τ_v is the atmospheric transmittance in the path from object to sensor, θ_i and θ_r are illumination and reflected light (observation) zenith angles, and φ_i and φ_r are azimuth angles, respectively. $\rho(\lambda, \theta_i, \varphi_i, \theta_r, \varphi_r)$ 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:

$$\mathrm{DN} = GA\Omega\tau \int_0^\infty L_{at\text{-}sensor}(\lambda)S(\lambda)d\lambda, \tag{4}$$

where G is system gain, A is the area of the detector, Ω is the lens solid angle (aperture), τ is the integration or exposure time, $S(\lambda)$ is the system level spectral response, and λ 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 (Beisl 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_{signal}) to noise electrons (n_{noise}) (Sandau, 2010):

$$\mathrm{SNR} = n_{signal}/n_{noise}. \tag{5}$$

Number of signal electrons can be given as

$$n_{signal} = (\Phi/h \cdot \upsilon) \cdot \tau \cdot A \cdot \eta, \tag{6}$$

where Φ is the intensity, $h{\cdot}\upsilon$ is the photon energy, τ is the exposure time, A is the area of the detector and η 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_{signal}), the CCD noise (n_{CCD}) (transfer, dark