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Study of Surface Brightness From Backscattered Laser Intensity: Calibration of Laser Data

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***Abstract*—Systematic laboratory measurements of laser backscatter intensity are presented for brightness calibration targets, and a calibration scheme for airborne laser scanner intensity data is proposed. Thus far, the use of these data has been partly hampered by the variability of the intensity with time, and no test fields have been available for airborne reflectance calibration. Portable brightness targets (tarps), with nominal reflectances from 5% to 70%, were manufactured, and, based on these measurements, found suitable for lidar reflectance standards. Furthermore, the variability of the recorded intensity from the tarps as a function of incidence angle was low. The measurements also provide new information on the surface albedo dependence of backscattering effects: as the surface brightness increases from 5% to 70%, the hotspot brightness peak amplitudes increase by 20% to 30%, and their apparent widths reduce to a half, which implies that hotspots could be used as an albedo discriminator.**

***Index Terms*—Backscattering, bidirectional reflectance distribution function (BRDF), hotspot, laboratory measurement, laser scanning, reflectance.**

I. Introduction

THE measurement of surface brightness for remote sensing targets is important for several applications. Land surface albedo is related to the absorption of solar radiation into the Earth's surface, which has a strong impact on the climate. Constant monitoring of long-term climatological variations calls for more accurate remote methods for surface albedo detection [1]. Glacier and ice surface albedo plays an important role in their surface energy balance, and hence in the hydrological and temperature variations in global scale [2].

Airborne laser scanning has become a well-established technique for the acquisition of digital data on surface topography (see [3] and [4] for an overview of applications). Exploitation of laser scanner intensity data would make one-shot surface topography and brightness information as well as aerial imaging possible. There have been a few attempts to combine these techniques in glacier monitoring and surface type classification [5]. The use of intensity in the retrieval of target characteristics is limited to, for example, being a predictor in tree species classification [6] or matching aerial imagery and laser scanner data. The more effective use of intensity values has not been possible partly due to the lack of calibration techniques. Due to the launch of laser scanners with a full-waveform option, there is a greater demand for establishing calibration methods for the intensity data. Converting the observed laser pulse intensity to surface reflectance requires the correction of atmospheric and directional variations, for which a simultaneous measurement of calibration targets would make up the most effective tool. Reflectance calibration targets for airborne measurements exist [7], but calibration targets for laser scanner intensity are largely missing. However, there is a synergy of photogrammetric calibration and airborne laser scanning calibration that can be used.

Knowing the reflectance properties of brightness targets is a prerequisite for their use in accurate intensity calibration. Such targets could also be used for quality analysis of aerial images and testing the linearity of airborne laser scanners. The sharp edge of the target can be used for resolving-power analysis of digital cameras in a similar way as it is for satellite images. The targets also enable the conversion of registered digital numbers (DN values) into ground reflectances that can be compared from different images. The scanning angle in laser scanners typically varies in the range of 0° to 20° off nadir causing a noticeable effect, especially on smooth surfaces. In smooth surfaces, such as lakes, the intensity varies with the incidence angle. It is thus required that the calibration target is insensitive to changes in the incidence angle.

Laser scanner instruments operate practically at exact backscattering (cf. [8]), where the angle between the source and viewing directions (i.e., the phase angle) is 0°. In optics the term "backscatter" refers to this particular direction, to separate from backward scattering, i.e., the reflection in the same hemisphere as the light source. There are strong directional properties of light reflection in this geometry, such as a strong increase in brightness toward the zero phase angle (the hotspot), which is a widely studied phenomenon in many fields of physics and optics [8]–[12]. Hotspots have recently gained more attention in the field of remote sensing because of new sensors which operate close to backscatter, such as POLDER and HyMap [10], [13]. Determination of the directional intensity effects at small phase angles provides both a source of calibration of small-angle data and a tool for target classification and characterization from remote observations. The effective use of such information requires a comprehensive laboratory reference study of backscattering from different targets, but such data are sparsely available for remote sensing purposes.

This letter presents small phase angle bidirectional reflectance distribution function (BRDF) measurements with linearly polarized laser for well-defined calibration targets. Our aim is to provide both a calibration method for airborne intensity measurements and new experimental information on the albedo dependence of hotspot, which is rarely studied, mainly because there is limited opportunity for controlled variation of a single parameter in the measurement of natural targets. The experiment and the targets are described in Section II. The results and their applications are discussed in Sections III and IV, respectively.

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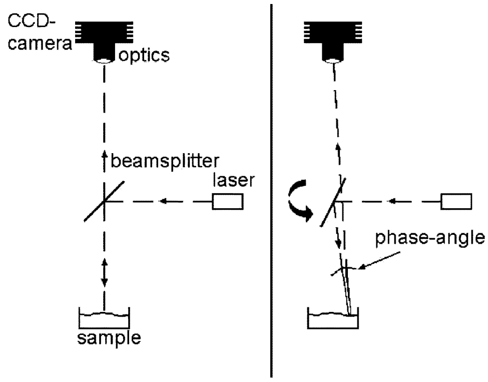

Fig. 1. Small-angle goniometer. Backscattered intensity is observed through a beamsplitter. Nonzero phase angles are obtained when the beamsplitter is rotated.

Fig. 2. Targets arranged in a line at the Sjökulla photogrammetric test field in Kirkkonummi (see [15] for more details) while testing a digital aerial camera. (Photo by H. Kaartinen, FGI.)

II. Experiment

A. Small-Angle Goniometer

The measurements were made with a small-angle goniometer [12] designed to work in scattering geometries similar to remote sensing instruments which observe at small viewing angles. The setup is based on techniques generally used for laser-based backscattering mesaurements in optics and condensed matter physics (see [8], [14] as well as [12] for more references). Backscattering geometry is worked out with a beamsplitter (see Fig. 1 for a sketch): the laser intensity reflected from the sample is monitored through the beamsplitter with a charge-coupled device (CCD) camera. Small phase angles around zero were achieved by rotating the beamsplitter to acquire a phase angle range of $-3°$ up to $10°$, (negative and positive signs come from measuring at both directions around $0°$ in the scattering plane) with the angular resolution of $0.4°$ (see [12] for more details). Since a setup of this type also causes the angle of incidence to change with phase angle, we also investigated the effect of incidence angle on the observed intensity (see Section III-A).

A sample rotator was used to smooth out the effects of laser speckle and to cover a larger sample area for the measurement as the spot moved along the rotating surface. Speckle effects were also reduced by averaging over several exposures (see [14] for further discussion on speckle in laser backscatter measurement in laboratory; the speckle effect in airborne laser measurements is thus far little studied): each data point in a phase curve is an average of five exposures. The average measurement error in terms of the standard deviations of these five shots was hence limited to about 2% for these targets. We also used a 0.1% transmission neutral density filter to keep the signal in the linear range of the CCD. The laser wavelengths were 632.8 nm (Helium-Neon) and 1064 nm (diode-pumped Nd:YAG), with polarization ratios of 500 : 1 and 100 : 1, respectively. The latter wavelength corresponds to that used by Optech and TopEye laser scanners.

B. Brightness Targets

The demand for targets large enough for airborne measurement has become evident after small-size targets were tested in aerial camera imaging. The material for such targets should be strong enough to endure hard field conditions when deployed occasionally over several years. The brightness targets used in this experiment were manufactured by Suojasauma Oy in Kuopio, Finland in 2000. The size of one target is 5×5 m. The tarps are portable and can be arranged in a straight line in a test field (see Fig. 2), and attached together with finger joints and composite poles (the number and combination of targets can thus be varied depending on the available space). Each tarp can be transported in a carrying bag with mounting poles, pulley tackles, and steel pegs. The tarps are stored in these bags in dry room conditions.

Eight targets with nominal reflectances of 5%, 10%, 20%, 25%, 30%, 45%, 50%, and 70% were manufactured, and their reflectances optimized at a wavelength range of 400–800 nm. As the reflectance values provided by the manufacturer were approximate, the demand for their more accurate laboratory calibration was crucially needed for their use in remote intensity calibration. The targets are made of polyester 1100 dtex with polyvinyl chloride (pvc) coating. The weight of the fabric is 600 g/m^2. They were coated with titanium dioxide and carbon black paint mixing pigments. A delustring agent was added to the paint to get a mat surface and to decrease the non-Lambertian reflectance effects. A mat surface does have its disadvantages; dirt attaches itself into the surface more easily in outdoor campaigns, and cleaning is more difficult.

Because of their relatively smooth surfaces and similarity in surface structure (Fig. 3), the test targets are well suited for the study of surface albedo effects on backscattering. Submillimeter-scale rough features as well as some narrow cracks in the surface can be seen in the microscopic images of some targets (Fig. 3). The reflectance spectra, plotted in Fig. 4, were measured using a flashlight system designed to work with an ASD FieldSpec Pro spectrometer. Both laser and spectrometer data were calibrated with a Spectralon (Labsphere, Inc.) reference plate; in case of phase curves, the average intensity value of Spectralon was taken from the linear part of its phase curve, because it also has a narrow brightening effect near zero in linearly polarized light.

III. Results and Discussion

A. Calibration of Laser Intensity

The measured phase curves for all eight targets at 1064 and 632.8 nm are plotted in Figs. 5 and 6. The reported nominal values are reproduced at about $2°$ to $3°$ phase angles at 1064

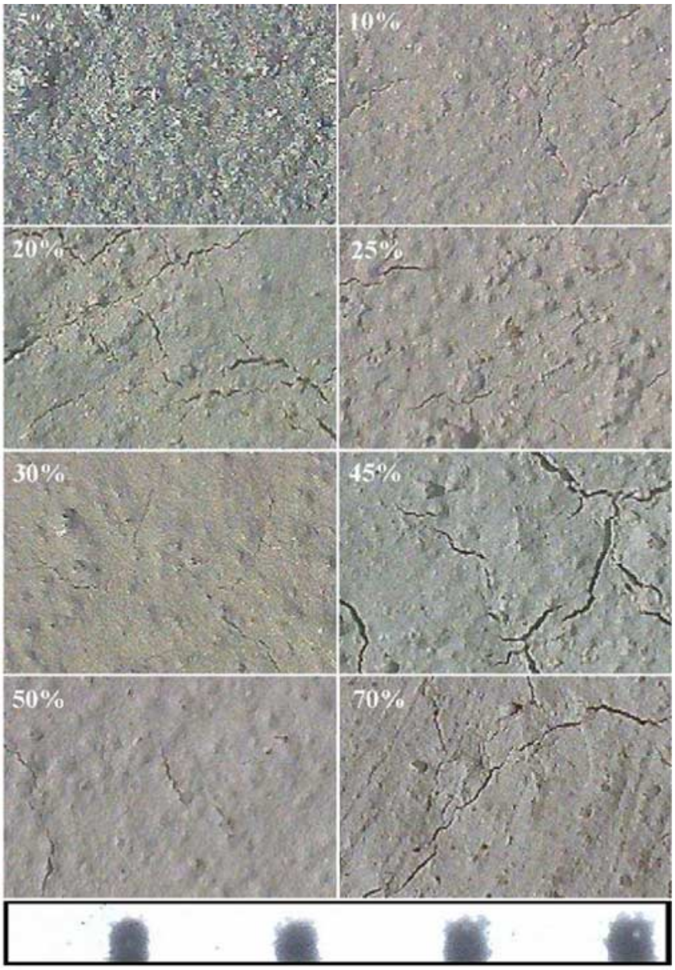

Fig. 3. Microscopic images of the surfaces of all eight targets reveal some rough fine structures. A millimeter scale is attached into the bottom of the image.

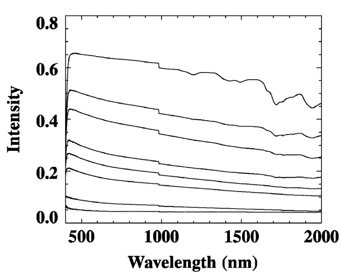

Fig. 4. Reflectance spectra of the targets, measured using a flashlight illumination placed right on top of each sample (i.e., the zenith) and the detector placed at about 30° from the zenith.

nm, whereas at 633 nm all samples are brighter than the nominal intensity (see Figs. 5 and 6). The spectra for all the targets, plotted in Fig. 4, show a slight decrease in reflectance toward larger wavelengths for all the samples (also note that in the reflectance spectra, the observed intensity values decrease to become smaller than the nominal ones as the wavelength increases). This partly explains the difference in the calibrated intensity values between 633 and 1064 nm. As the scattering properties of these tarps are far from being isotropic, the calibration intensity will always depend somewhat on the way it has been measured. Any remote calibration with the tarps is therefore relative and well-establishded laboratory calibration is important for them in each application. The reflectance of Spectralon, which was used to calibrate the intensity of the test tarps (see Section II-B), is also affected by linear polarization, which may also have affected the result. Further discussion on more accurate (polarimetric) calibration of both laboratory and airborne laser measurements would be worthwhile. Our future objective is to extend the experiment to investigate polarization effects near the zero phase.

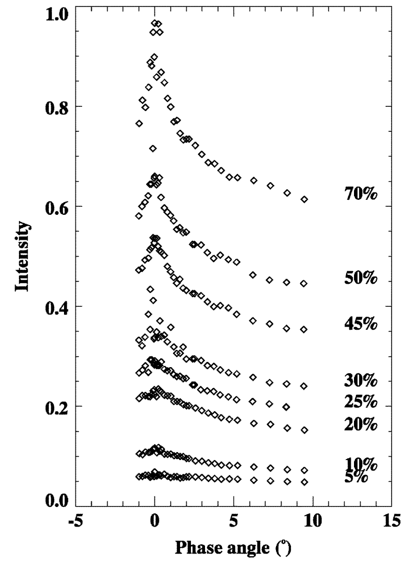

Fig. 5. Reflectance phase curves (relative to Spectralon) for all eight targets at 1064 nm.

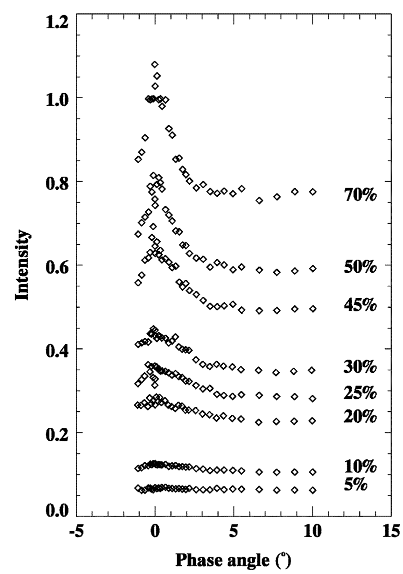

Fig. 6. Reflectance phase curves (relative to Spectralon) at 632.8 nm.

At phase angles greater than 5° (where we assume the hotspot to be no more predominant), the relative differences between targets correspond with the nominal ones at both wavelengths. The intensity fractions $(I(0°))/(I(5°))$ in Table I provide an estimate of the directional corrections that are needed to eliminate the effect of hotspot from the calibrated intensity. As the deviation in data was smaller at the brighter end of the brightness range, the use of, for example, three to four of the brightest targets (and then averaging the results) would provide a practical means of brightness calibration.

TABLE I
BACKSCATTERING PEAK AMPLITUDES (A) AND HWHM PHASE ANGLES FOR ALL SAMPLES AT 1064 AND 632.8 nm. THE AMPLITUDES ARE COMPUTED FROM THE EXPONENTIAL FIT AS $(I(0°))/(I(5°))$

Sample	A 1064	A 632.8	HWHM 1064	HWHM 632.8
5%	1.18	1.06	1.8°	1.4°
10%	1.41	1.15	1.7°	1.8°
20%	1.33	1.19	1.7°	1.7°
25%	1.34	1.24	1.7°	1.6°
30%	1.34	1.25	1.7°	1.6°
45%	1.39	1.30	1.4°	1.2°
50%	1.36	1.37	1.3°	0.8°
70%	1.44	1.39	1.0°	0.9°

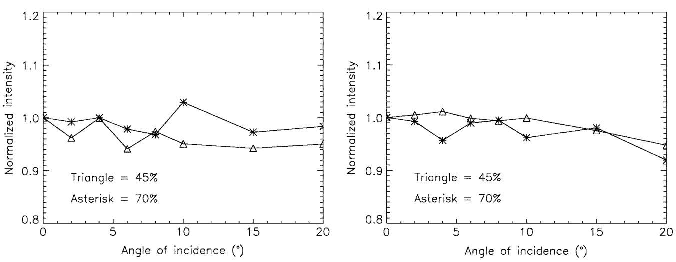

Fig. 7. Effect of incidence angle ι on backscattering at (left) 1064 nm and right) 633 nm. Measurements are presented for the 70% and 45% samples and normalized to unity at $\iota = 0°$.

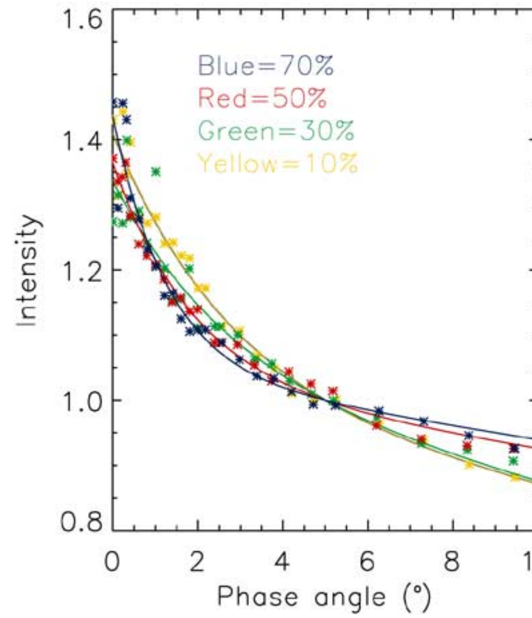

Fig. 8. Reflectance curves for 10%, 30%, 50%, and 70% targets at 1064 nm. The curves are normalized to $I(5°) = 1$ for easier comparison of peak properties.

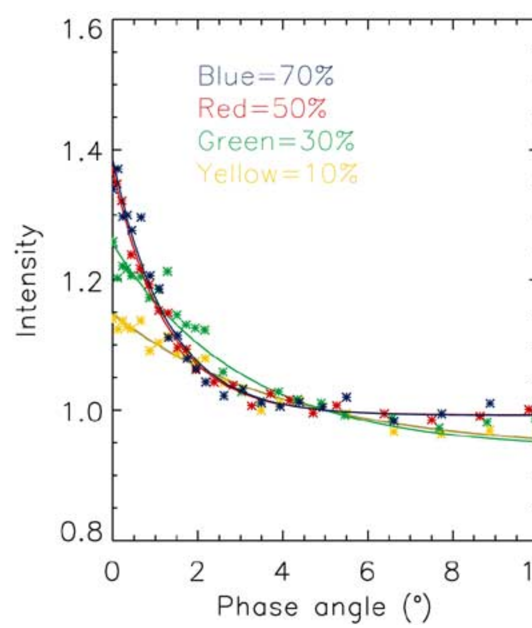

Fig. 9. Reflectance curves (as in Fig. 8) at 632.8 nm.

To test the feasibility of the targets for the airborne calibration of laser scanner measurement, where the angle of incidence (with respect to the surface normal) varies by several degrees, we studied the target intensity as a function of incidence angle ι to the sample. The intensity was monitored at 0° using a tilt table to change ι to vary between 0° and 20°. The trends, if any, were within the error range of the experiment up to 10° to 12° (Fig. 7), which is the range of the incidence angle of the small-angle goniometer. A decrease of a few percent occurs at 633 nm between 15° and 20° (the measurement error is large, however, because of the manual sample rotation with the tilt table). The graphs in Fig. 7 also imply that the specular reflection at 0° incidence is negligible.

B. Effect of Surface Brightness on Backscatter

Figs. 5 and 6 show the observed intensity levels for all targets plotted in the same frame, which causes the hotspot peaks for lower intensity targets to appear flatter than those for bright samples. The relative increase in brightness seems stronger in the infrared than in the visible (red) wavelength. For a more accurate comparison of peak properties, we carried out an empirical modeling procedure: a simple exponential function was fitted in the data in order to compare the intensity levels at a particular angular range (i.e., to smooth out the noise in data to enable a more accurate classification), and to measure the half-width at half-maximum (HWHM, cf. [11]) phase angles more precisely. The function gives the intensity $I(\alpha)$ as a function of the phase angle α in the form: $I(\alpha) = a\exp(-(\alpha/d)) + b + k\alpha$ (where a, d, k, and b are empirical parameters). Examples of fits are plotted in Figs. 8 and 9, where all the curves are normalized to $I(5°) = 1$ for easier comparison of peak widths and heights. We computed the amplitudes and widths (HWHMs) of the brightness peaks (in Table I) using the $I(\alpha)$ values at 0° and 5° (where we assume the hotspot effect to be negligible). Deviations from the monotonic trend are most likely to be caused by inaccuracy in the measurement near zero (visible in Figs. 5 and 6 and more pronounced at 632.8 nm), where a small angular error results in great uncertainty in the intensity because of the extreme sharpness of the peak. This implies that the experimental study of hotspot must rely on ample supply of data to compensate for any random errors present in a single measurement.

Table I (and Figs. 8 and 9) shows an increase in peak amplitude as nominal reflectance increases. The amplitude also increases between 632.8 and 1064 nm, although the reflectances are greater at 632.8 nm. The coherent backscattering effect is expected to dominate the hotspot in wavelength-sized structures [9] and to become more intense as the increase in brightness enhances multiple scattering. This is consistent with our observation that the peak amplitudes increase with increasing reflectance, but there seems to be a wavelength effect as well. The HWHM values decrease toward the brighter targets at both wavelengths, and this trend appears slightly stronger at 632.8 nm (see also Fig. 9). HWHM variation with brightness is greater than that between wavelengths. The coherent backscattering models predict that HWHM should be linearly proportional to the wavelength, but there is only a slight decrease between 1064 and 632.8 nm (cf. [11] and references therein). It is obvious that backscattering models still do not explain completely the hotspot characteristics.

IV. Conclusion and Applications

We investigated the directional properties of brightness calibration targets for the purposes of laser scanner intensity calibration and the physics of light backscattering. Surface brightness has a clear effect on the backscattering peak amplitude and width at both wavelengths studied. Comparison with earlier results [11], [12] suggests that other surface characteristics dominate over albedo on the optical properties in backscatter. One of the future objectives is to find out whether the influences from different parameters can be separated to get, at least with some *a priori* information on the target, a method for the remote retrieval of surface albedo. The effect of albedo may also depend on which of the scattering mechanism dominates the hotspot, but a further understanding of the physical nature of hotspot still requires more work.

These targets facilitate the relative calibration of airborne intensity measurements, as, for example, the use of Spectralon reference panels in various laboratory applications (including the present study and, for example, [7], [11], and [12]). This letter provides information on the correction of their directional (non-Lambertian) scattering properties at small angles, which is essential for instruments operating at backscatter. The effect of incidence angle on these targets was found to be negligible, which also makes it possible for them to be used as a brightness reference.

Laser scanner intensity information, which has been little used until recently, would enable better classification of laser points and help the separation of tree species and surface types. According to [16] the use of full-waveform in an airborne laser scanner would offer the possibility of classifying the data based on the shape of the echo. It is also expected that it will be possible to use the waveform in the creation of more accurate digital terrain models. Strong, narrow echoes correspond to hits from building roofs and from unvegetated terrain. Classification of such hits is possible with waveform data but would, however, require more precise calibration of the intensity data. Calibration can be carried out by means of portable tarps in surveys where ground reference stations are also used. Separate calibration flights, such as those carried out with aerial cameras at the beginning of each season in Finland, are also possible. The characteristics of the tarps can then be checked under laboratory conditions using the instrumentation described in this letter, and the directional correction can be applied. The results of the present study show that the painted tarps are almost of ideal calibration reference for the laser intensity at both applied wavelengths. It should be noted that the wavelengths of the laser scanners may vary (between, for example, 1.0 and 1.6 μm) and the characteristics of the tarps need to be verified at the same wavelength range.

The directional correction of the laser intensity for a large set of remote sensing targets will be discussed in our forthcoming paper. We are also planning to apply the calibration procedure in an airborne application to be able to estimate and improve the accuracy of the intensity measurement. We are developing the instrument so that will be able to measure the effects of polarization, to establish a solid method for high accuracy laser intensity measurement, and to contribute to a better comprehension of the physics of backscattering effects.

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