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Retrieval of glacier surface albedo using terrestrial photography

Détermination de l'albédo de surface des glaciers à partir de photographies terrestres

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Corripio a développé en 2002 une méthode pour la détermination de l'albédo des glaciers à partir de photographies terrestres. Cette méthode permet un suivi de la variabilité spatio-temporelle de ce paramètre déterminant dans le bilan de masse des glaciers. Deux appareils photographiques numériques ont été installés à cet usage sur le glacier de Saint Sorlin (Alpes, France) complétant ainsi l'instrumentation météorologiques et glaciologiques du site. La méthode développée par Corripio a été mise en application sur ce glacier et améliorée par l'utilisation d'une base de données de Réflectance Bidirectionnelle de la neige (BRDF), établie à partir de mesures en laboratoire, afin de prendre en compte l'anisotropie du rayonnement réfléchi par la surface du glacier. L'évolution spatiale et temporelle de l'albédo du glacier a été étudiée durant l'été 2006 à partir des photographies terrestres et de mesures d'albédo en un point sur le glacier ; ces données indiquent que la méthode originale accompagnée d'un traitement de l'anisotropie permet une détermination des valeurs d'albédo très cohérente. Cependant, cette méthode nécessite un point d'albédo de référence (mesuré) sur le glacier. Afin de s'affranchir de cette nécessité, une nouvelle méthode a été développée incorporant un traitement spectral des rayonnements incident et réfléchi, une conversion bande étroite à bande large, la prise en compte de l'anisotropie du rayonnement réfléchi et permettant ainsi un traitement absolu sans la nécessité d'un point de référence. Ce papier présente les principes et les résultats pour l'été 2006 de la méthode originale ainsi que les bases de la nouvelle méthode.

The use of terrestrial photography to determine snow surface albedo has been developed by J. Corripio in 2002. This method allows an easy determination of spatio-temporal variability of this parameter which is decisive in glacier mass balance. Two digital cameras have been settled for this intent on the Saint Sorlin glacier (Alps, France) in order to complement meteorological and glaciological monitoring instruments. Corripio's method has been applied on Saint Sorlin glacier and improved using a database of Bidirectional Reflectance Distribution Function (BRDF) of snow in order to take into account anisotropy of snow radiative transfer. This database has been built using BRDFs of different types of snow measured in laboratory. Spatial and temporal evolution of glacier albedo has been derived during summer 2006 using terrestrial photography and surface albedo measurement on one point of the glacier ; these data show that the original method improved with reflected radiation anisotropy processing allows coherent retrieval of albedo values. Nevertheless, the original method requires an albedo reference point (measured) on glacier. A new method based on Corripio's original method has been also developed in order to avoid the necessity of an albedo reference point. This method includes several improvements, spectral processing of incident and reflected radiation, narrow-to-broadband conversion, anisotropy treatment and so allows absolute retrieval of surface albedo value without the necessity of an albedo reference point. This study described the results obtained during summer 2006 with the original method but also the principles of this new method.

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I ■ INTRODUCTION

In the scope of understanding relationship between glacier and climate and to assess glacier melting, measurement of precise annual glacier mass balance is essential. In the Alps, this surface mass balance is mainly governed by variations in surface albedo, α, defined as the ratio of reflected shortwave radiation to incident shortwave radiation. This parameter varies in space (surface of snow, ice or rock debris) and time (new to old snow, ice, time of the day) on the glacier and its variations lead to slowing or increasing ablation rate. Thus a precise knowledge of its value is essential for the accurate assessment of glacier energy (and then mass) balance.

As surface glacier albedo shows a high temporal and spatial variability, measurement of punctual glacier albedo at a reasonable and thus limited number of stations may not be representative of the global surface [1]. Satellite, aerial or terrestrial remote sensing seems to be an adequate way to retrieve glacier surface albedo. These techniques allow a global view with high spatial and temporal sampling and then make many glaciers and large areas measurable.

This study aims at presenting a method for retrieving glacier surface albedo from terrestrial photography. After a description of the site chosen for validation, the principles of the original method developed by Corripio [2] are exposed and solutions to the issues raised by the original method are proposed, enlighting the milestones of a new method. Lastly, this study presents the results obtained with the original method on Saint Sorlin glacier during summer 2006.

II ■ VALIDATION SITE

Saint Sorlin glacier (Grandes Rousses area, Western Alps, France) *[Figure 1]* has been chosen for validation of the method. Saint Sorlin glacier covers a 3 km^2 area. The glacier's tongue is around 2 700 m a.s.l and its top (Etendard peak) nearly reaches 3 500 m a.s.l. The mass balance of this glacier has been monitored by Laboratoire de Glaciologie et de Geophysique de l'Environnement at Grenoble (LGGE) since several decades (1957). All information on this site is available at http://www-lgge.ujf-grenoble.fr/ServiceObs/.

A permanent Automatic Weather Station (AWS) has been settled on the moraine (2 700 m a.s.l.) since 2005. The AWS is provided among others with radiation measurements devices (shortwave and longwave), wind, temperature and humidity sensors. A standard digital camera also takes automatically three photos of the glacier per day since 2005 from the hut located near the tongue. During summer 2006 an AWS has been settled on the glacier and measured albedo using a CNR1 Kipp & Zonen sensor measuring incident and reflected shortwave radiation.

An additional near-IR digital camera (modified Canon EOS 400D camera) has been settled near the visible camera in 2008 to allow spectral processing of reflected radiation ; and two AWS provided with radiation devices have been fixed up on the glacier on the ablation and accumulation area, at places visible on the photography. These two stations are needed for the validation of the new method exposed in this study.

III ■ METHODOLOGY

The original methodology to retrieved albedo from terrestrial photography has been developed by J. Corripio [2].

III.1 BASIS

A digital elevation model[2] of the glacier as well as ground control points allow georeferencing of the photography. The method requires atmospheric data for computation of solar irradiance and horizontal transmitivity, and at least one albedo reference point (this means a pixel of the photography where the glacier albedo is measured). With these data, one is able to convert the Digital Number of pixel (RGB values) into albedo values.

This method is quite operational ; nevertheless it raises different issues.

The first one is that the albedo value needed for the calculation of energy balance is an integrated value over the solar spectrum (most significant part of it is from 0.3 to 2.8 μm). However the albedo value 'measured' by the camera is a narrow band value : the measurement is in fact done only in the sensitive bands of the camera CMOS sensor which are far from being a continuum over the solar spectrum (*Table 1* and *Figure 2*). That is why a narrow to broad band conversion is

2. Here we will use a Digital Elevation Model of Saint Sorlin Glacier established in 2003.

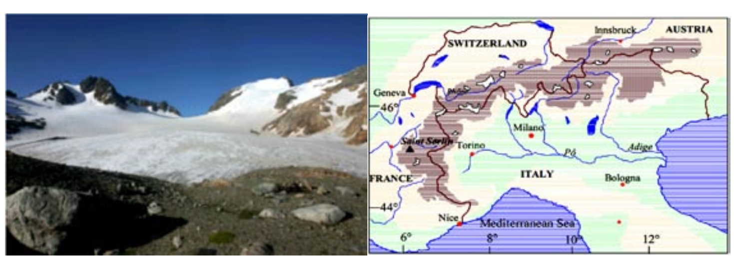

Figure 1 – Left : St Sorlin glacier. At the right upper corner of the photography stands the Etendard peak (3 464 m a.s.l). This photography is taken from the hut located near the tongue of the glacier. This photography was taken by the visible camera at the end of July 2006. The near-IR camera is located at the same place and takes photography from the hut. Right : Map of the Alps (C. Vincent) with location of Saint Sorlin glacier.

Table 1 – Canon EOS 5D and modified 400 D spectral sensitivity. The spectral bands given in this table are the maximum sensitivity bands of the camera for each pixel of the Bayer filter (two green, one red and one blue). Each channel fits with a pixel of the Bayer filter.

Camera type	Channel 1 and 4 (green)	Channel 2 (blue)	Channel 3 (red)
Visible camera (EOS 5D)	440 to 500 nm	500 to 560 nm	570 to 630 nm
Near IR camera (modified EOS 400D)	680 to 740 nm	800 to 860 nm	640 to 700 nm

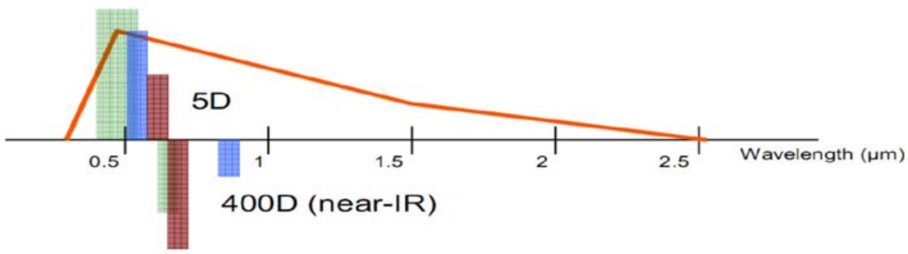

Figure 2 – Schematic view of solar spectral irradiance (upper curve) and maximum spectral sensibility bands for each channel of EOS 5D (up) and modified EOS 400D (down).

needed. In the original method, this conversion is implicitly done by applying the reference albedo[3] but induces a non negligible error (up to 0.2 on albedo value). So a spectral treatment and a proper conversion are needed to retrieve accurate albedo value.

Secondly, as explained above, the original method requires the measurement of an albedo reference value. In order to extend the use of this method to many glaciers and to minimize the number of ground devices needed to measure reference albedo, it would be appreciable to avoid the need of this albedo reference value. This could be easily done considering the camera as an absolute intensity sensor, and calibrating it for this use. To achieve this task, a greater attention has also to be paid to model accurately the incident radiation.

Lastly, the albedo value used in the energy budget is the ratio of hemispherical reflected radiance to hemispherical incident irradiance. However, the camera is an angular sensor, which means that it measures the radiation reflected into a limited solid angle which is not equal to a whole hemisphere. Therefore it is necessary to convert this measured angular value into an hemispherical value. This conversion would have been trivial if snow and ice were Lambertian[4] surfaces. The reflection behaviour of snow and ice has to be known is order to perform this conversion.

III.2 SOLUTIONS

In this section, solutions to the problems raised above are presented. For more clarity some of the variables used in the section are precisely defined in nomenclature at the end of the text.

To perform a proper spectral conversion, a spectral solar irradiance model which computes incident solar radiation with respect to date, time, place and atmospheric parameters, Spectral2 [3], was implemented. This spectral model is consistent with the measurement of the moraine AWS and also with the previous integrated solar irradiance model, Iqbal [2] (less than 5 % relative difference between the three types of hourly data – Spectral2, Iqbal and AWS- for a typical summer clear sky day over St Sorlin glacier hourly data). So one is now able to compute accurately incident irradiance using Spectral2 and atmospheric value of the moraine AWS (temperature, visibility and relative humidity extrapolated at any elevation).

Besides, reflected radiance has also to be processed spectrally. In this scope, the two cameras spectral sensitivity, $h(\lambda)$, have been measured using a monochromatic light source. *Table 1* gives the maximal spectral sensitivity bands for the two cameras. This calibration allows to calculate image integrated irradiance, E_i, from image spectral irradiance, $l_i(\lambda)$, as explained in equation *(1)*.

$$E_i = Q_i \int_{\Delta\lambda} h(\lambda) l_i(\lambda) d\lambda , \qquad (1)\ [4]$$

where Q_i denotes a calibration coefficient.

Secondly, for the camera absolute intensity calibration, photography of Lambertian surface of known reflectance (Labsphere® samples) has been taken while measuring the intensity of incoming solar radiation. Since the CMOS sensor is not in its saturation range, the response is quite perfectly linear (correlation coefficient from linear regression higher

3. It assumes that pixel's albedo is proportional to pixel RGB value indeed modified (by Bidirectional Reflectance Distribution Function, topography, ...) [2].

4. Lambertian surfaces reflected the same amount of radiation whatever the direction of reflection.

than 0.999) and sensitivity varies with channel (colour) and adjustments of the camera[5]. Based on this experiment, one can compute f, the response function of the camera which link the Digital Number of the pixel B_i, with the image irradiance, E_i. Finally, the image spectral irradiance, $l_i(\lambda)$, can be easily retrieved (assuming for example that, h is a sum of Dirac functions) using equation *(2)*.

$$\int_{\Delta\lambda} h(\lambda) l_i(\lambda) d\lambda = \frac{1}{Q_i} f^{-1}(B_i), \qquad (2)\ [5]$$

The last problem was to convert an angular reflectance to an hemispherical reflectance. In this scope, we did numerous measurements of snow Bidirectional Reflectance Distribution Function (BRDF) to study the anisotropy of snow and ice reflection. These measurements have been performed using the spectro-gonioradiometer of Laboratoire de Planétologie de Grenoble ([6], [7]). The principle is quite simple ; a sample is illuminated with monochromatic radiation for different incident zenith angles and the instrument measures the radiation reflected by the sample for various zenith and azimuth observation angles. *Figure 3* shows an example of anisotropy factor. On this chart, one can notice that snow BRDF is characterized by a strong forward scattering peak as previously noticed in [8] and values of anisotropy factor are quite high. According to the observation angles, the reflectance value can be multiplied by a factor greater than 2, thus the errors induced while considering that snow and ice reflection are isotropic are not negligible. This set of measurements allows building a database of snow anisotropy factor to be used to convert the angular value of albedo measured via the camera into an hemispherical value useful in energy balance studies. This database is not the subject of this paper and will be published later.

5. One adjustment is chosen for the whole summer for each of the cameras.

All these improvements give access to six different spectral irradiance values (three wavelengths per camera) meaning six values of $l_i(\lambda)$ function. To convert this value into a value over the solar spectrum ($\int_{0..3\mu m}^{2.8\mu m} l_i(\lambda) d\lambda$, *(3)*), we use the transfer radiative model DISORT [9], optimising the distance between the six data points and the modelled spectral albedo curve.

Figure 4 gives a summary of all the necessary stages to convert RGB values into energetic albedo values.

IV ■ PRELIMINARY RESULTS

In this section, preliminary results obtained from summer 2006 pictures on Saint Sorlin glacier are presented. Albedo maps have been retrieved using the original method (with reference albedo point given by an AWS on the glacier) complemented with angular correction (use of snow and ice anisotropy factor).

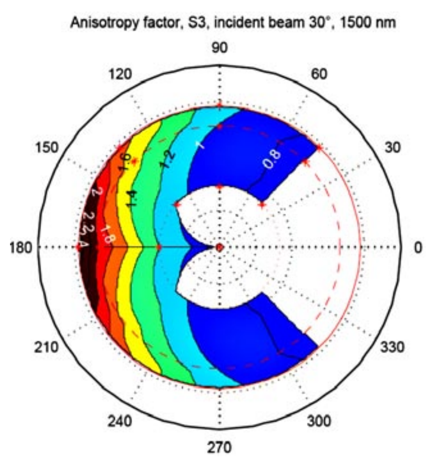

Figure 3 Anisotropy factor measured at 1 500 nm for a sample of snow. The incident zenith angle is 30º. On this chart the polar radius is proportional to the zenith observation angle and the polar angle is the relative azimuth angle between incident beam and observation

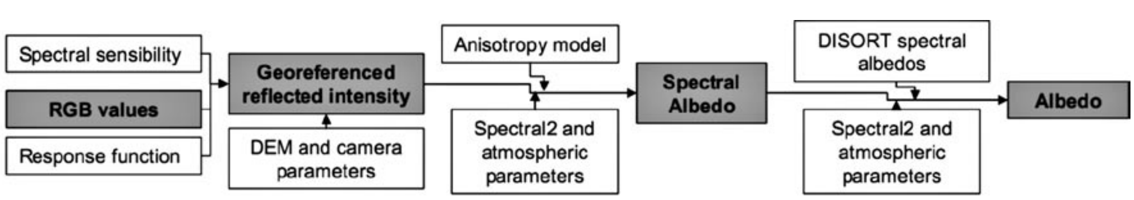

Figure 4 – From Digital Number of pixel to energetic albedo value.

Figure 5 shows retrieved albedo maps from 31 July to 23 August 2006. The top of the glacier is at bottom left of the map and the tongue at the top of the map. At the end of July, the surface of the glacier is mainly constituted of black ice ($\alpha \in [0.15;0.2]$). After the 17th of August snow precipitation event, one can notice the progressive melt of snow ($\alpha \in [0.4;0.7]$) except for high altitude places (bottom left).

To test the coherence of retrieved albedo values, the temporal evolution of one point around 3 400 meters high (point A on *Figure 5*) which is covered with snow after the 17th of August and one point at the bottom of the glacier (point B on *Figure 5*, around 2 800 m a.s.l.) are analysed *(Figure 6)* using a set of four photographs. A classical parameterisation ([10], [11], [12]), for the evolution of albedo after snowfall is :

$$\alpha = \alpha_{firn} + (\alpha_{freshsnow} - \alpha_{firn})e^{-\frac{n_d}{n^*}} \qquad (4)$$

where n_d is the number of days after significant snowfall and n^* is a characteristic time scale of melt.

A basic fit between our data points and this parameterisation gives a very good correlation coefficient ($R^2 = 0.98$).

Table 2 gives a comparison of our retrieved coefficients (α_{firn}, $\alpha_{freshsnow}$ and n^*) to Knap's coefficients ([11], [12]) for a whole year of study on Morteratschgletcher. The agreement is strong for the two albedo values but the two time scales are really different. This strong difference can be easily explained by the fact that Knap's values are average values for one year (including winter when melt is weak ; the thickness of snow to be melt is not the same that for our case) but Saint Sorlin values are restrained to a unique episode of melt during the ablation season.

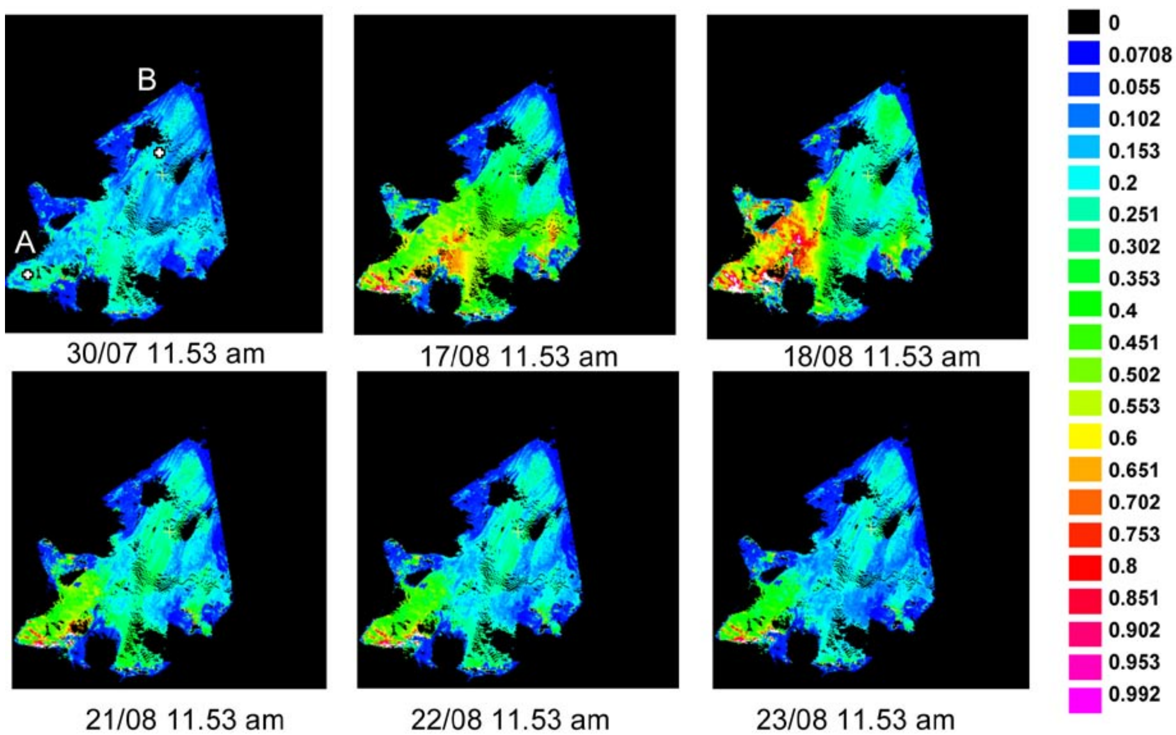

Figure 5 – Retrieved St Sorlin glacier albedo maps for a few days of summer 2006. Top of the glacier (Etendard Peak) is at the bottom left of the maps. Black pixels (null albedo) are the locations which are not apparent on the photography.

Table 2 – Comparison of regression coefficents for Morteratschgletcher (annual) and St Sorlin glacier (August 2006) for equation (4). Coefficients for Morteratschgletcher are taken from Coefficients for Saint Sorlin glacier are the results of fitting equation (4) with the albedo values of point A (Figure 5) for 18, 21,22 and 23th August 2006.

Site	α_{firn}	$\alpha_{freshsnow}$	n^***(days)**
Morteratschgletcher	0.54	0.763	21.3
St Sorlin	0.52	0.71	1.535

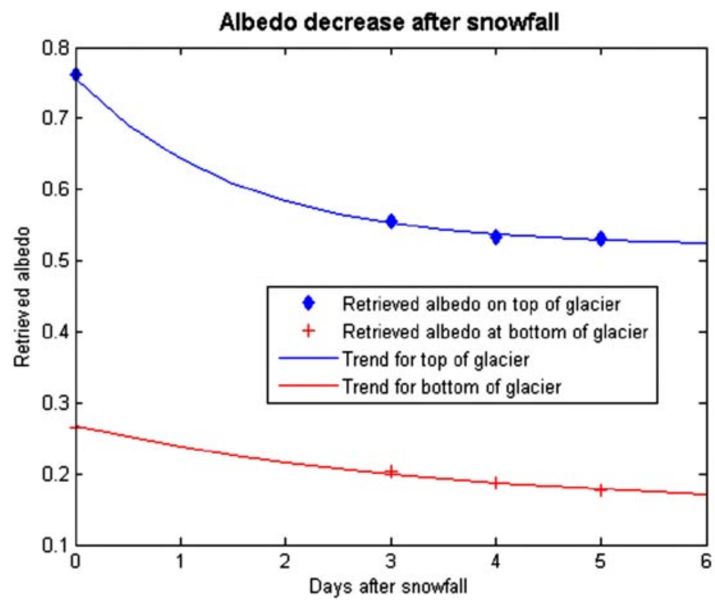

Figure 6 – Temporal evolution of top (A) and bottom (B) glacier albedo after 17th August 2006. Trends are fit of equation *(4)*. Coefficients are given in *Table 2*.

V ■ CONCLUSIONS

Retrieving surface glacier albedo from terrestrial photography seems to be a promising method. Improvements of original method (spectral processing, narrow-to-broad-band conversion, anisotropy treatment and absolute retrieval) should allow an accurate retrieval of surface albedo values on glaciers without ground measurements.

These values could be use for at least two different purposes :

• Computation of distributed energy (and then mass) balance

• Albedo values assimilation into a numerical model of snowpack evolution (CROCUS)

The advantages of using such a method to retrieve albedo values are numerous. First it does not require expensive devices to perform the measurements in the field. Then cameras can take pictures automatically, which avoids constraining and repetitive terrain measurements. And finally, the camera covers the whole glacier ; one can easily imagine that this method should allow the survey of more than one glacier since it can be settled on other glaciers than Saint Sorlin glacier.

VI ■ NOMENCLATURE

Variable	Symbol	Definition
Camera Spectral sensibility	$h(\lambda)$	Normalized value of the ratio of Digital Number to the intensity of the incident monochromatic light at wavelength λ, for the same pixel of the photography
Image integrated irradiance	E_i	Radiation intensity measured by the camera on the whole spectrum (0.3 to 2.8 μm) at pixel i
Image spectral irradiance	$l_i(\lambda)$	Radiation intensity measured by the camera at wavelength λ, at pixel i
Digital Number	B_i	Digital value of pixel i, from 0 to 4 096 in 12 bits scale
Bidirectional Reflectance Distribution Function (BRDF)	ρ	Ratio of reflected radiation into an infinitesimal solid angle to the incident radiation into an infinitesimal solid angle
Anisotropy Factor	R	Ratio of BRDF to spectral albedo (hemispherical), i.e. normalized BRDF which allows comparison of anisotropic behaviour even if spectral albedo values are different

VII ■ ACKNOWLEDGEMENTS

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